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CAPILLARY RISE AND CAPILLARY MOVEMENT OF MOISTURE IN FINE SANDS

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In agricultural science, interest in the capillary movement of moisture in soils has shifted nowadays from the height of capillary rise in dry soils to the driving force or capillary potential inducing movement into partly wetted soils (6, 7, 16, 18). Nevertheless, the height of capillary rise is an important quantity, since it decides the relative scale of capillary potentials in comparing any two soils or sands, and, further, if the capillary rise and the permeability of a sand are known, it is possible to solve completely any problem involving the advance of a water-front into the dry sand. The aim of the present paper is to show that the height of capillary rise is calculable from the particle size and the porosity of a fine sand. At the end of the paper, it is pointed out that the permeability may be calculated from the same data, and the foregoing points are applied to theoretical calculations of the upward capillary movement of water into an initially dry sand.

Across a curved air-water interface, a pressure difference exists which at any point is given by $\sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$ dynes/cm.^{2}, where R_1 and R_2 are the principal radii of curvature at the given point, and σ dynes/cm. is the surface tension of the interface. In a vertical capillary standing in water, a curved surface or meniscus is formed, and a "capillary rise" takes place until the hydrostatic pressure balances the pressure difference due to curvature. In the following work, it is assumed throughout that the following two conditions hold true; first, the water makes zero angle of contact with the walls of the capillary; second, the capillary section is so small that we can neglect the effect of gravity on the curvature of the meniscus. Then, in a circular capillary of radius r cm., we can assume that the meniscus is hemispherical, so that $r = R_1 = R_2$, and the pressure difference is $\frac{2\sigma}{r}$. If this is balanced by a capillary rise, measured from the plane water surface outside the capillary to the bottom point of the meniscus, h cm., we get, neglecting the density of air,

$$\rho g h = \frac{2\sigma}{r} \quad \text{or} \quad h = \frac{2\sigma}{\rho g r} \tag{A}$$

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Similarly, for plane, parallel, vertical plates, distance $2b$ cm. apart, $R_1 = b$ and $R_2 = \infty$,

so that $$h = \frac{\sigma}{\rho g b} \qquad (B)$$

For an elliptical section with semimajor axis, a, and semiminor axis, b, we may take $R_1 = a$, $R_2 = b$,

so that $$h = \frac{\sigma}{\rho g}\left(\frac{1}{a} + \frac{1}{b}\right) \qquad (C)$$

Equation (C) would also hold for a rectangle with sides $2a$ and $2b$. For an equilateral triangle or a square, the principal radii at the bottom of the meniscus will be approximately equal to the radius, r_i, of the inscribed circle,

so that $$h = \frac{2\sigma}{\rho g r_i} \qquad (D)$$

Now it is desirable to replace the various expressions for $\left(\dfrac{1}{R_1} + \dfrac{1}{R_2}\right)$ for sections of different shapes by a single quantity which, though perhaps not mathematically accurate, has a general significance and is not limited to regular shapes. This is possible by rediscussing capillary rise from a more familiar angle, i.e., as representing an equilibrium between an upward force due to surface tension acting over the perimeter, and a downward force due to gravity acting over the area of the cross-section, i.e., $\sigma \times$ perimeter $= \rho g h \times$ area

or $$h = \frac{\sigma}{\rho g m} , \qquad (E)$$

where m is the ratio of area to perimeter, or also, since the capillary section is uniform,

$$m = \frac{\text{volume of column of water in capillary}}{\text{area of wetted surface of capillary}} , \qquad (F)$$

which will prove of more service when we turn to sand beds.

To give some idea of the approximation obtained, the following table compares values of $\dfrac{1}{m}$ with values of $\left(\dfrac{1}{R_1} + \dfrac{1}{R_2}\right)$ as substituted in equations (A) and (E). If we compare equations (A) and (E), it will be seen that $2m$ is the radius of a circular capillary with the same ratio of perimeter to area as the given noncircular capillary, so that, for comparison, values of $\dfrac{2}{r_e}$ are included in the table, where r_e is another equivalent radius, namely, that of a circular capillary with the same cross-sectional area as the given capillary. Finally,

to show departure from circular shape, values of $4\pi \times \dfrac{\text{area}}{(\text{perimeter})^2}$ are included, these being unity for a circle. Similar values are shown in table 1.

	$\left(\dfrac{1}{R_1}+\dfrac{1}{R_2}\right)$	$\dfrac{1}{m}$	$\dfrac{2}{r_e}$	$4\pi \times \dfrac{\text{AREA}}{(\text{PERIMETER})^2}$
Circle.......................	$2/r$	$2/r$	$2/r$	1.00
Parallel plates.................	$1/b$	$1/b$	0.0	0.0
Ellipse $\begin{cases} a:b=2:1\dots \\ a:b=5:1\dots \\ a:b=10:1\dots \end{cases}$	$1.50/b$	$1.54/b$	$1.41/b$	0.84
	$1.20/b$	$1.34/b$	$0.89/b$	0.45
	$1.10/b$	$1.30/b$	$0.63/b$	0.24
Rectangle.....................	$1/a + 1/b$	$1/a + 1/b$	$\sqrt{\pi/ab}$	$\pi ab/(a+b)^2$
Equilateral triangle...........	$2/r_i$	$2/r_i$	$1.21/r_i$	0.61
Square.......................	$2/r_i$	$2/r_i$	$1.77/r_i$	0.79

These values show that $\dfrac{2}{r_e}$ is completely out of the question and that $\dfrac{1}{m}$ gives a remarkable number of accurate values. Even for very narrow, elliptical capillaries, the $\dfrac{1}{m}$ value is not more than 20 per cent in error. It seems exceedingly likely that it will give reasonable values for capillary rise for most shapes of capillary. A very similar position arises in hydrodynamics, where m is termed a "hydraulic radius," and represents a balance between skin friction and pressure loss in pipes and channels. By replacing radius of circular pipes with $2m$ in formulas, a good correlation has been achieved for noncircular pipes, although a rigorous mathematical treatment is not possible.

The only experimental data for noncircular capillaries are those of Schultze (19, 20), who carried out measurements of capillary rise of water in a number of capillaries of very varied sections. In each case, he cut the capillary at the level of the bottom of the meniscus, took a photomicrograph of the cross-section at a magnification of 100, and measured its area and perimeter. The ratio of these gives m, and the values of mh in the last column of table 1 should be constant and equal to 0.074, the value of $\dfrac{\sigma}{\rho g}$ for water at 20°C. The agreement is actually not better than 10 per cent, but in view of the wide range of cross-sectional shapes involved, this can be regarded as a decided success for equation (E).

An important observation made by Schultze was that, in noncircular capillaries, the edge of the meniscus is by no means level and, where capillary walls form a sharp angle, the edge of the meniscus shows a sharp local rise to a considerable height above the bottom of the meniscus. This behavior of the meniscus has important consequences, especially when we turn to sand beds. In these, the capillary passages show an extreme degree of angularity, and therefore the "meniscus effect" plays an extremely important role. It enables moisture to creep far above the normal capillary height, and conditions

between the bottom and upper edge of the meniscus correspond to a partly wetted sand or soil, i.e., to conditions under which capillary potentials are measured.

In an earlier treatment of capillary rise in sand beds, Keen (11) made use of Slichter's calculations (22) on the permeability of a bed of uniform spheres.

TABLE 1

Data of Schultze for capillary rise of water in noncircular capillaries

	AREA OF CROSS-SECTION	PERIMETER OF CROSS-SECTION	m	h	mh
	$cm.^2$	$cm.$	$cm.$	$cm.$	$cm.^2$
	Nearly circular sections				
1.01	0.0145	0.425	0.0341	2.1	0.0715
1.03	0.0088	0.328	0.0268	2.75	0.0735
0.98	0.0053	0.261	0.0203	3.5	0.071
1.00	0.0039	0.221	0.0176	4.2	0.074
1.07	0.0032	0.194	0.0165	4.85	0.08
1.01	0.00213	0.163	0.0130	5.7	0.074
0.91	0.00166	0.151	0.011	6.2	0.068
0.98	0.0015	0.139	0.0108	6.7	0.072
Average of 8 values..					0.0735
	Very irregular sections				
0.68	0.0101	0.433	0.0233	2.75	0.064
0.93	0.0076	0.320	0.0237	2.95	0.070
0.78	0.0053	0.293	0.0181	3.5	0.063
0.76	0.00655	0.329	0.0199	3.95	0.0785
0.88	0.0031	0.210	0.0147	4.85	0.0715
0.52	0.00455	0.333	0.0136	4.82	0.066
0.80	0.00307	0.220	0.0139	5.4	0.0755
0.76	0.00246	0.201	0.0122	5.7	0.0695
0.82	0.0019	0.170	0.0112	6.7	0.075
Average of 9 values..					0.0695

The figures in the extreme left column are $4\pi \times \dfrac{area}{(perimeter)^2}$, which is unity for a circle; the departure from unity gives an idea of the departure of the cross-section from circular shape.

The latter assumed that the pore space was equivalent to a bundle of triangular, parallel capillaries, and calculated the dimensions of these. Keen used the values so obtained to substitute in equation (A) for r, making suitable corrections for the noncircular shape of the capillary. The equation obtained was

$$h = \frac{19.8\sigma}{\rho g d} \qquad\qquad (G)$$

where d cm. is the particle diameter. Smith, Foote, and Busang (23) followed similar lines, but they modified Slichter's calculations.

If, however, equation (E) can give a reasonably accurate correlation of capillary rise in noncircular capillaries, it is likely that it will also be applicable to the capillary channels in a sand bed. Suppose that ϵ = porosity or fractional free volume of the bed, and that S = particle surface in square centimeters per cubic centimeter of volume occupied by the sand bed. Now, if the sand grains are in random packing, any cross-section of infinitesimal thickness will have the same porosity, ϵ, and therefore the fractional pore area of the cross-section will also be ϵ. Thus, a liquid rising through the bed will undergo changes of direction, but will flow through a channel of constant, average cross-sectional area, equal to a fraction, ϵ, of the whole cross-section of bed normal to direction of flow. Some writers have contended that the fluid stream must undergo continual contractions and expansions as well as changes of direction, i.e., that the fractional cross-sectional area of the bed varies from point to point. This would be true of, say, uniform spheres in a regular mode of packing but is completely contradictory to the concept of random packing. Even if the average free cross-sectional area is taken as constant, it is argued that individual capillaries in the bed are not of constant section, but expand and contract alternately along their length. While this is true, it is utterly wrong to judge a system of capillaries completely interconnected at every level by the behavior of a single capillary of variable section. It does, however, have one important effect which will be discussed in the experimental section.

Now, for channels of uniform cross-sectional area, we can calculate m by equation (F). In a bed of length, L cm. and cross-sectional area, A cm.^{2}, the area of the wetted surface is LAS, and the volume occupied by the liquid is $LA\epsilon$, whence $m = \dfrac{LA\epsilon}{LAS} = \dfrac{\epsilon}{S}$, and, substituting in equation (E),

$$h = \frac{\sigma S}{\rho g \epsilon} \qquad (H)$$

If S_0 is the particle surface per unit solid volume, i.e., the specific surface, then $S = (1 - \epsilon) S_0$. For spherical particles of uniform size, $S_0 = \dfrac{6}{d}$, and therefore

$$h = \frac{\sigma S_0 (1 - \epsilon)}{\rho g \epsilon} = \frac{6(1 - \epsilon)}{\epsilon} \cdot \frac{\sigma}{\rho g d} \qquad (I)$$

which may be converted to

$$\frac{\rho g h d}{\sigma} = \frac{6(1 - \epsilon)}{\epsilon} \qquad (J)$$

Hackett and Strettan (9), using a bed of spherical particles, for which the aver-

age porosity was 0.38, found that $\dfrac{\rho ghd}{\sigma}$ was practically constant for four different liquids and had the average value 9.6. The calculated value is

$$\frac{6 \times 0.62}{0.38} = 9.8.$$

Smith, Foote, and Busang (23) tested a wide variety of liquids in sand beds, using three different types of particle, and plotted $\dfrac{\rho ghd}{2\sigma}$ versus ϵ, over the range $\epsilon = 0.33$ to $\epsilon = 0.45$. Though their results are somewhat scattered, they nearly all lie between the curves given by $\dfrac{\rho ghd}{\sigma} = \dfrac{6.5(1 - \epsilon)}{\epsilon}$ and $\dfrac{8(1 - \epsilon)}{\epsilon}$. Thus it would appear that the specific surface of the sand grains lay between $S_0 = \dfrac{6.5}{d}$ and $S_0 = \dfrac{8}{d}$, and these limits are, indeed, in agreement with the gen-

TABLE 2

Atterberg's data on capillary rise in sands

SIZE RANGE	AVERAGE SIZE, d	ϵ	m	h	mh
cm.	*cm.*			*cm.*	
0.5 –0.2	0.35	0.382	0.0253	2.5	0.063
0.2 –0.1	0.15	0.385	0.0110	6.5	0.072
0.1 –0.05	0.075	0.418	0.00635	13.1	0.083
0.05 –0.02	0.035	0.416	0.00293	24.6	0.072
0.03 –0.02	0.025	0.42	0.00213	34.0	0.073
0.02 –0.01	0.015	0.426	0.00131	42.8	0.056
0.01 –0.005	0.0075	0.444	0.00071	105.5	0.075
0.005–0.002	0.0035	0.468	0.00036	200(?)	0.072

eral run of natural sands, as examined by permeability tests and by microscope (3, 5).

Atterberg (1) investigated the capillary rise of water in a series of sands of different sizes, and obtained the results given in the first, third, and fifth columns of table 2. The arithmetic average size, d, for each sand is given in the second column, and $m = \dfrac{\epsilon}{S} = \dfrac{\epsilon}{S_0(1 - \epsilon)}$ is calculated in the fourth column, assuming $S_0 = \dfrac{8.5}{d}$. In the last column, the product, mh, by equation (E) should be equal to 0.075, the value of $\dfrac{\sigma}{\rho g}$ for water at 17°C. Since it is not certain that the arithmetic mean is the true mean size, or that the equation $S_0 = \dfrac{8.5}{d}$ makes proper allowance for the nonspherical shape of the grains, it can be regarded as satisfactory that the values of mh are of the right order, and that they are reasonably constant over a hundredfold variation in particle size.

As the foregoing evidence is not sufficiently complete, the writer carried out some experiments in which was measured the capillary rise of several liquids in a bed of spherical glass particles and in three different sizes of sand.

<div align="center">EXPERIMENTAL</div>

As already pointed out, noncircular capillaries show a marked rise of the edge of the meniscus where the cross-section forms sharp angles. In sands, this is greatly magnified, as shown by the way water can creep into sands and soils without completely filling the pores. The detailed description of this creep and its practical significance with respect to capillary potentials has been discussed fully by others (6, 7, 10, 16). In the present work, the aim was to eliminate its effects as much as possible. As water rises in a sand column contained in a vertical glass tube, it is observed that the lower part of the column is definitely filled with water, and above this, lies an indefinite region in which the sand is damp and which seems capable of almost indefinite extension at a slow and decreasing rate. The capillary rise, corresponding to the "bottom of the meniscus" in a capillary tube, must lie at the interface between the partly filled and the completely filled region, but this cannot be fixed with any exactitude by visual inspection. In addition to meniscus effects, capillary rise in sands is subject to marked hysteresis, so that a minimum capillary rise has been observed with an advancing water column, and a maximum rise with a receding column. The latter is the value with which we are concerned here, but a receding column only enhances the practical difficulties.

In the present work, the most successful method of eliminating meniscus effects and hysteresis was not to measure a height of capillary rise, but to measure the air pressure required to force liquid below the surface level of the sand bed. The two quantities are equivalent, since the curvature of the meniscus in a capillary, and the pressure difference across it, are the same whether that pressure difference is balanced by an air pressure or by a hydrostatic pressure due to capillary rise.

Apart from these difficulties, however, it must be remembered that, although $m = \dfrac{\epsilon}{S}$ has a constant value at all cross-sections, it represents only an average capillary size in any individual section. If the liquid level of the completely filled part of a sand column could be viewed under a microscope, it would be not dead level, but above the average level in narrow capillaries and below in large capillaries. Similarly, air will begin to enter the bed surface at large capillaries before it begins to advance into the bed over the whole section. As should be expected, the method does not give a sharp and unequivocal value for capillary rise, and it is essential to distinguish a capillary rise which corresponds to the mean value for the bed and therefore to $m = \dfrac{\epsilon}{S}$. The way this was done is described in the following.

The successful apparatus was that shown in figure 1. Tube A, 2.1 cm. in diameter is connected to the capillary tube B, 0.2 cm. in diameter. Both are half-filled with liquid, and a known weight of sand is run onto the support C, sufficient to give a depth of 2–3 cm. This is compacted to its minimum porosity by gentle tapping, thus ensuring that the surface porosity at D is the same as the average porosity of the bed, and measurement of its height enables the porosity to be calculated. Excess liquid is run off by tap T until there is no liquid above the sand, and the liquid in B is level with D. Then T is closed and the rubber stopper E, carrying a glass tube, is inserted in tube A. A is connected to a manometer M by the side-arm shown, and the glass tube in E is connected to a reservoir R, into which mercury can be run slowly. The stream of mercury is started, causing a slow rise of pressure in A, and the level in B is watched. As soon as this level shows any movement, the stream of mercury is slowed to produce a barely perceptible rate of rise of pressure, and readings of the levels in B and on the manometer are taken simultaneously. The relative sizes of B and of A are such that a very slight movement of liquid in the sand bed gives a large movement in B.

The following data are the results of a typical experiment, in this case, for the capillary rise of benzene in sand B:

h_m	h_B	$h = (h_m - h_B)$
26.1	0.2	25.9
31.8	0.4	31.4
33.4	0.6	32.8
34.5	0.8	33.7
35.2	1.0	34.2
35.6	1.2	34.4
36.1	1.4	34.7

The first and second columns are simultaneous readings on the manometer, h_m, and in B, h_B, the manometric reading being converted to an equivalent head of benzene. The third column gives the actual pressure drop at the air-liquid interface in the surface of the sand bed D, i.e., $h = (h_m - h_B)$. Now, if the height of capillary rise in a sand bed were perfectly definite, and the meniscus retreated uniformly from D, then each increase in h_m would be counterbalanced by an equal increase in h_B, so that h would first rise to a value equal to the capillary height and then remain constant. As was to be expected from the previous discussion, the meniscus does not retreat evenly, and therefore it is still somewhat difficult to fix on a suitable value of h to express capillary rise.

The difficulty is decreased by plotting h_B versus h, taking gradients on the resulting curve and plotting these against h. As seen by figure 2, the curve of $\frac{dh_B}{dh}$ versus h shows a much sharper bend than that of h_B versus h, and there is a very rapid rise as $\frac{dh_B}{dh}$ approaches and exceeds 0.5. This is readily understood by reference to the ideal case, since, if h were constant when h_m and h_B in-

creased, then $\dfrac{dh_B}{dh}$ would be infinite. The method adopted, therefore, was to construct the curve of h_B versus h, and to read off the value of h corresponding to a gradient of 0.5 on this curve. The choice of gradient was arbitrary, since values from 0.4 to 1.0 might equally well be chosen to denote the region in which $\dfrac{dh_B}{dh}$ rises rapidly for small increases in h. If such values had been chosen, all the values of h would have been decreased or increased by a few per cent; but any consistent value of the gradient would have given equally good reproducibility for the same sand and same liquid, and equally good correlation between different sands and different liquids.
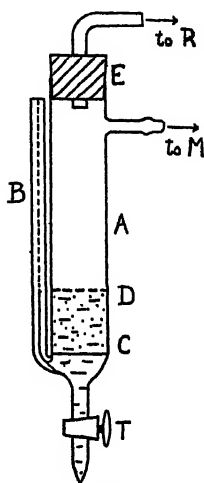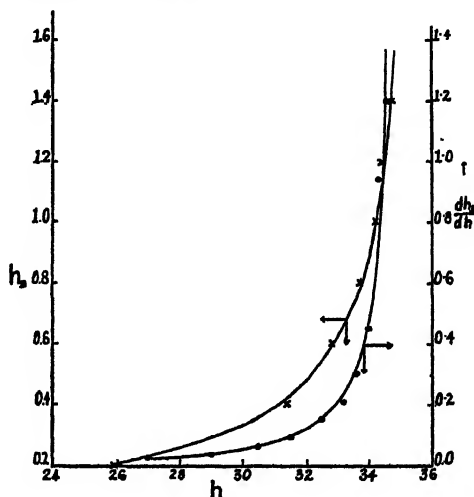
FIG. 1   FIG. 2

FIG. 1. APPARATUS FINALLY USED TO MEASURE PRESSURE DROP ACROSS AIR-LIQUID INTERFACE OR CAPILLARY RISE IN A SAND

FIG. 2. CURVES OF h_B AND OF $\dfrac{dh_B}{dh}$ VERSUS h FOR BENZENE IN SAND B

RESULTS

The first experiments were carried out with small spherical glass particles, prepared by the method of Sklarew (21). As these were perfect spheres, the specific surface could be obtained accurately by microscopic analysis. The size-distribution, based on a count of 1000 particles, was as follows:

SIZE RANGE	AVERAGE SIZE IN RANGE, d	NUMBER OF PARTICLES IN RANGE, N
μ	μ	
10–40	25	90
40–60	50	261
60–90	75	307
90–110	100	266
110–140	125	76

Then, since the total surface is $\pi \Sigma N d^2$, and the total volume is $\frac{\pi}{6} \Sigma N d^3$,

the specific surface is $S_0 = \frac{6 \Sigma N d^2}{\Sigma N d^3}$, which leads to a value of 655 cm.²/cc.

This was used to calculate the theoretical values of h in equation (I), and the calculated and theoretical values are given in table 3. The surface tension was checked for each liquid by measuring the rise in a circular capillary 0.304 mm. in diameter.

The specific surface for the three sands could not be determined by the microscope, since one would need to know the shape of the particles. Recently, however, it has been shown that specific surface can be calculated from the

TABLE 3

Results of experiments on height of capillary rise

SUBSTANCE	LIQUID	$\dfrac{\sigma}{\rho}$	h (OBSERVED)	h (CALCU-LATED)
			cm.	cm.
Glass spheres ($\epsilon = 0.375$)..	Carbon tetrachloride 18°C. (2 expts.)	17.0	19.0	18.9
	Acetone, 18°C. (3 expts.)	30.3	34.5	33.8
	Benzene, 18°C. (3 expts.)	32.8	35.9	36.5
	Water, 18°C. (3 expts.)	73.0	83.0	81.5
Sand A ($\epsilon = 0.375$).......	Carbon tetrachloride 17.5°C. (2 expts.)	17.0	9.75	10.3
	Tetrachlorethane 16°C. (3 expts.)	23.0	13.6	14.0
	Ethyl ether, 16°C. (4 expts.)	25.2	14.8	15.3
	Ethyl alcohol, 17°C. (3 expts.)	28.8	16.8	17.5
	Acetone, 17°C. (3 expts.)	30.4	17.4	18.5
	Benzene, 16°C. (3 expts.)	32.9	19.7	20.0
	Dilute acetic acid (4 expts.)	54.0	33.0	32.9
	Water, 16°C. (3 expts.)	73.2	43.4	44.6
Sand B ($\epsilon = 0.40$)........	Acetone, 23°C. (2 expts.)	29.7	30.7	30.7
	Benzene, 23°C. (2 expts.)	32.5	33.9	33.6
Sand C ($\epsilon = 0.36$)........	Water, 23°C. (2 expts.)	72.3	11.5	11.7

permeability, K_1, and the porosity, ϵ, of the sand (4). The equation relating these quantities is

$$K_1 = \frac{g}{5 S_0^2} \cdot \frac{\epsilon^3}{(1 - \epsilon)^2} \qquad (K)$$

or, conversely, since $g = 980$ cm./second,

$$S_0 = 14 \sqrt{\frac{1}{K_1} \cdot \frac{\epsilon^3}{(1 - \epsilon)^2}} \qquad (L)$$

K_1 is obtained by forming a bed of the sand of thickness, L cm., cross-sectional area, A cm.², and porosity, ϵ. A liquid of viscosity, η poises, is forced through

the bed under a pressure drop, ΔP gm./cm.^{2} If the rate of flow is Q cc./second, then the permeability is given by the equation,

$$\frac{Q}{A} = u = K_1 \frac{\Delta P}{\eta L} \tag{M}$$

where u cm./second is the apparent linear velocity of the liquid through the bed. Application of this method to the spherical glass particles gave $S_0 = 648$ cm.^{2}/cc., in satisfactory agreement with the value obtained by microscopic examination.   The values of S_0 for the three sands proved to be 358 cm.^{2}/cc. for sand A, 675 cm.^{2}/cc., for sand B, and 89 cm.^{2}/cc. for sand C.   Values of h calculated from these, together with the experimental values, are given in table 3.

In comparing the calculated and observed values in table 3, the main point to be observed is the correlation for all liquids, sizes of particle, shapes of particle, and porosities studied.   Too much emphasis must not be placed on the actual agreement between any one calculated value and its corresponding observed value, since the "observed" values could all have been increased or decreased simultaneously by a few per cent by taking a different arbitrary value of the gradient, $\frac{dh_B}{dh}$.   The value of 0.5 for this gradient was chosen partly to give the best all-round numerical agreement with the values calculated by equation (I).

The results in table 3, however, do show that equation (I) gives the capillary rise with as much certainty as it can be measured and that it expresses the correct relationship between the variables involved.

APPLICATION TO UPWARD CAPILLARY MOVEMENT OF WATER

If the capillary rise, h, and the permeability, K_1, of a fine sand are known, it is possible to solve somewhat idealized problems involving capillary movement of a liquid into the dry sand.   The conditions for a mathematical treatment are, first, absence of hysteresis; second, uniform advance of the water-front, filling pores completely as it moves; third, tightly packed sand to prevent displacement of grains on wetting.   A problem of this type arises if we suppose the sand overlies a water table, and it is required to find the maximum height of capillary rise and the rate at which water rises into the initially dry sand at say, 20°C.   Given h and K_1, this problem has been adequately discussed by many workers (2, 12, 13, 14, 15, 17, 24).   The only novelty of the present solution lies in the calculation of h by equation (I) and of K_1 by equation (K) from the specific surface, S_0, and the porosity, ϵ, of the sand.

Suppose we consider three sizes of particle, representing the lower size limits, respectively, of silts, 2μ, of fine sand, 20μ, and of coarse sands, 0.2 mm.   It will be supposed that the particles are spherical, so that S_0 has the values, 30,000 cm.^{2}/cc., 3,000 cm.^{2}/cc., and 300 cm.^{2}/cc., and that the typical porosi-

ties are, respectively, $\epsilon = 0.50$, $\epsilon = 0.45$, and $\epsilon = 0.40$. Then, from equation
(I), one obtains

$$h = \frac{\sigma S_0(1 - \epsilon)}{\rho g \epsilon} = 0.074 \frac{S_0(1 - \epsilon)}{\epsilon} \qquad (N)$$

substituting $\dfrac{\sigma}{\rho g} = 0.074$ for water at 20°C., and we get

SUBSTANCE	ϵ	h	h
		cm.	feet
Coarse sand.................	0.40	33.3	1.09
Fine sand..................	0.45	271	8.9
Silt.......................	0.50	2220	72.8

If, in time t seconds, the water-front has risen to a height of x cm., then,
by equation (M),

$$u = K_1 \cdot \frac{\Delta P}{\eta x} \qquad (O)$$

But u is the apparent linear rate of rise, whereas the actual rate of rise through
the sand bed, $\dfrac{dx}{dt}$, will be $\dfrac{u}{\epsilon}$, assuming that the fractional free area of the cross-
section of the bed is equal to the porosity, ϵ. Also as the capillary force is the
sole driving force, ΔP will be equal to $\rho(h - x)$, where ρ gm./cc. is the density
of the liquid, so that

$$\frac{dx}{dt} = \frac{u}{\epsilon} = \frac{K_1}{\epsilon} \cdot \frac{\rho(h - x)}{\eta x} = \frac{K_1}{\epsilon} \cdot \frac{100(h - x)}{x} \qquad (P)$$

substituting $\dfrac{\eta}{\rho} = 0.01$ for water at 20°C. Now, by equations (K) and (N),

$$\frac{K_1}{\epsilon} = \frac{g}{5 S_0^2} \cdot \frac{\epsilon^2}{(1 - \epsilon)^2} = \frac{1.07}{h^2} \qquad (Q)$$

so that equation (P) becomes

$$\frac{dx}{dt} = \frac{107}{h^2} \frac{(h - x)}{x} \qquad (R)$$

Integrating, this gives

$$h \ln \left(\frac{h}{h - x} \right) - x = \frac{107 t}{h^2} \qquad (S)$$

Substitution in equation (S) gives the following results:

x	x (APPROX.)	t COARSE SAND	t FINE SAND	t SILT
cm.	*feet*	*min.*		
30	1	8.1	20.4 min.	145.4 min.
120	4	...	1.02 days	50 days
240	8	...	4.4 days	17 weeks
610	20	...	....	52.5 weeks
1100	36	...	....	105 weeks
2100	69	...	....	9.4 years

In equation (S), x and t are in centimeters and seconds, respectively, and these have been subsequently converted to feet, minutes, hours, etc.

Because of what have been denoted as meniscus effects, the water-front will not advance as a solid front as postulated above, and it will be able to creep to heights much exceeding h. Even so, the foregoing tabulation serves a very useful purpose, since it does give the correct order of magnitude of the heights attainable and of the comparative times required to reach a given height. The latter are particularly instructive, for, though the capillary driving force is much greater in a fine sand than in a coarse one, water actually enters the latter at a faster rate. Equally, of course, a fine-pored system which is saturated with water is less easily drained.

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FACTORS INFLUENCING EXCRETION OF NITROGEN BY LEGUMES[1]

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The claim that inoculated legumes can excrete nitrogen compounds is supported by definite and reliable evidence, yet the negative results appearing in the literature are just as frequent and convincing. Ample justification exists for the view that, not only is the universal occurrence of the phenomenon doubtful, but also that excretion occurs only under special conditions. Balancing the positive findings as reviewed by Nicol (9, 10) and Virtanen (13) against the negative ones as summarized by Wilson and Burton (16) and Wilson (17) most likely fails to give a true picture of the experimental results, since the publication of negative data unfortunately is frequently neglected. The fact that Virtanen and his collaborators consistently obtain positive results whereas other investigators report a mass of negative and contradictory evidence suggests that a special set of, as yet incompletely defined, relationships between the plant and its environment controls the occurrence of the excretion phenomenon. The present work has been directed toward the determination of these factors. Since, as has already been indicated (17), the large majority of our experiments are negative, it would serve no useful purpose to report them in detail. Instead, the major phases of the research will be summarized with the view that our experience may aid others in defining the conditions necessary for obtaining excretion and that some clarification of the present confused picture may result.

EXPERIMENTAL

Methods

The methods used were essentially those described by Wilson and Burton (16). Experiments have been conducted since 1937 in several of the station's greenhouses and out-of-doors in favorable seasons. Several workers participated independently in the experiments reported here. In the trials with open pots the techniques observed in routine legume inoculation work were

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employed, i.e., the sand and seeds were sterilized at the outset of the experiment, and precautions were taken to maintain sterility throughout the work. At harvest the plants were washed from the substrate, the species separated, and dry weight and total nitrogen determined. For direct detection of excreted nitrogen the fine roots were screened from the sand, 100-gm. aliquots of the sand were digested in macro-Kjeldahl flasks, and triplicate flasks were distilled into one measure of standard acid. In this manner reasonable checks on replicate determinations could be obtained.

Type of experiment

In an attempt to duplicate the work of Virtanen, every effort was made to follow as closely as possible his methods of plant culture. Most of our experiments were conducted with peas, although other legumes were used, including vetch, soybeans, broad bean, cowpeas, alfalfa, and the clovers. None of the legumes gave consistent excretion, although doubtful and positive results were occasionally obtained. The large-seeded legumes such as soybeans offer special difficulty in that significant quantities of nitrogen may diffuse from the seed during germination and thus give falsely positive results. In the experiment shown in plate 1, sudan grass is benefited from its association with soybeans. Because the soybeans germinated slowly, a duplicate experiment was made in which all soybean seedlings were carefully removed as soon as they appeared above the sand. The sudan grass in association made an excellent growth and at harvest contained an average of 42.7 mgm. N per pot of 10 plants; the controls grown alone contained only 13.0 mgm. N per 10 plants. Ten sudan grass plants were sown with five large soybean seeds; the excess nitrogen evidently came from these during germination. The exudations of nitrogen which benefited the sudan grass occurred long before any nitrogen fixation could have occurred.

Clovers have been used in some experiments, at times with definite excretion, but the difficulty of separating and harvesting the companion crop led us to abandon these legumes for our extensive routine experiments. As a result of a large number of trials it was concluded that peas and vetch offered the greatest possibility for success.

Through the courtesy of Professor Virtanen we obtained samples of Finnish peas, barley, oats, and the sand used at his station. With these materials experiments have been performed at our station which apparently duplicate exactly those made at Helsinki, in addition to parallel experiments in which local types of sand, varieties of plants, and strains of bacteria have been used. Several such experiments have been completed during the past few years, but as noted by Wilson (17), few positive results were obtained. From the results of these tests, we have concluded that selection of the proper plant, bacteria, sand, and container does not guarantee the *occurrence* of excretion although it is possible that each factor may influence the *quantity* of excretion if and when it does occur.

Although the presence of a nonlegume is not necessary for excretion, most of the work at the Wisconsin station has been with associated cultures, since the nonlegume provides a convenient indicator for detection of the phenomenon. Scholz (12) claims, however, that in his experiments significant quantities of nitrogen were excreted into the sand (2 mgm./100 gm.), but this nitrogen was not utilized by the oats or rye plants in association. Obviously, the plant used for this purpose must develop in about the same period of time as the legume, it must respond readily to nitrogen fertilization, and it must not be inhibitory to the normal development of its companion crop. In our work, oats and barley were found to be satisfactory for experiments with peas and vetch, and rye grass associates well with clover. In some experiments in which peas were associated with potatoes, the latter definitely inhibited the growth of the former. In a like manner, bluegrass at times failed to grow in harmony with clover.

An increase in the nitrogen content of sand in which inoculated legumes had been grown was observed in several cases. It is necessary to examine critically data from such experiments, since the nitrogen determination is frequently on such a small fraction of the total substrate that the multiplication of experimental error by a large factor may lead one to false conclusions. A difference of at least 1 to 2 mgm. *per sample analyzed* would appear to be the minimum for basing claims of positive excretion. Madhok (6) reports positive excretion in a culture from which he was able to leach only 0.5 mgm. of N from 2 kilos of sand over a period of 90 days.

Type of container

In a recent communication Virtanen and Torniainen (14) emphasize the necessity of using porous pots as plant containers because aeration of substrate is an important factor in controlling excretion. As has been pointed out by Ludwig and Allison (4), the fact that excellent excretion has been obtained in glass suction flasks at the Finnish station obviously weakens the argument. Nevertheless, experiments were undertaken to determine whether this factor was the cause of the negative results at the Wisconsin station. In most of our work since 1936 burnt clay pots very similar to those used at Helsinki have been employed. Using the porosity test suggested by Virtanen and Torniainen, we found that many of these were even more porous than those which gave positive results at Helsinki. From a large group of new red clay pots obtained from a local kiln, ten of the most porous and ten of the least porous were selected. In an experiment with peas and oats the results in all pots were uniformly negative.

Period of growth

When barley and oats were grown alone in the nitrogen-poor sand used in our experiments, they responded readily to small quantities of nitrogen added at any time during the growth period. Consequently in associated cultures

one should readily detect excretion at any time during the growth of the legume by the response of the nonlegume. But when sand analysis is used as the criterion of excretion, it is important to select the proper time of harvest.

Figure 1 shows the quantity of nitrogen found in the substrates of inoculated peas, vetch, and soybeans which were analyzed periodically throughout the growth period. The peas and vetch showed maximum excretion at the end of the seventh week, whereas the soybean showed no significant excretion throughout the growth period. The disappearance of the nitrogen from the substrate probably arises from its reabsorption by the legume. The finding of large quantities of nitrogen in the sand at the blossoming time of the peas corresponds to the period of maximum fixation. Scholz (12) also found that quantities of nitrogen in the substrate of pea and lupine cultures or in mixed
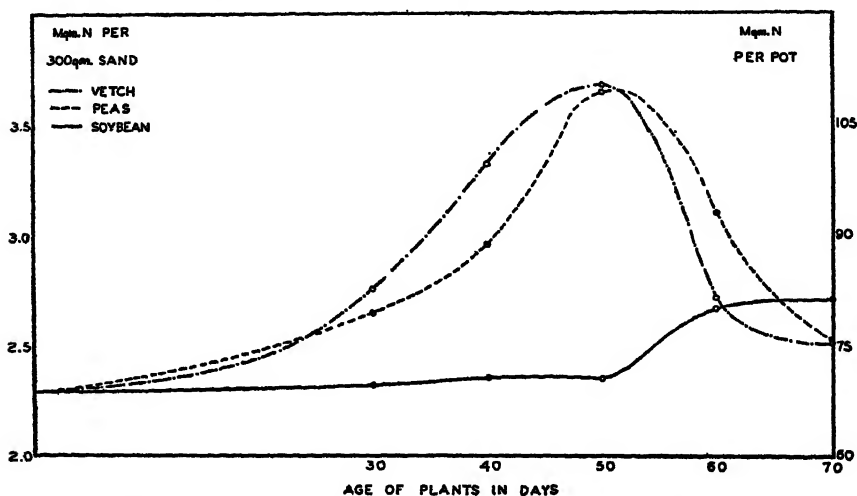
FIG. 1. NITROGEN FOUND IN SAND SUBSTRATE DURING GROWTH OF VARIOUS LEGUMES

cultures of the legumes with rye and oats increased until late in the growth period and then decreased. Scholz, however, observed little benefit to the associated nonlegume even though large quantities of excreted nitrogen were present in the substrate. He suggests that microorganisms in the soil tie up the nitrogen as it is excreted and render it unavailable. It appears unlikely that this should be done quantitatively and that the nonlegume roots should fare so badly in competition with the bacteria for the nitrogen. In fact, the presence of bacteria admits the possibility of nonsymbiotic nitrogen fixing organisms as an alternative explanation.

Role of the carbohydrate-nitrogen relationship

The failure to confirm consistently the results of Virtanen in spite of every effort to duplicate his methods suggests that the widely differing climates at the two stations may provide a reasonable explanation of the discrepancy.

Observations on the meteorological conditions and the type of growth during our occasionally positive experiments have supported the view advanced by Wilson and Wyss (15) that the relation between photosynthesis and nitrogen fixation, as controlled by the environment, may be the dominant factor. This view implies that excretion is a mechanism of the plant by which a "normal" carbohydrate-nitrogen balance may be maintained. For example, under certain environmental conditions carbohydrate synthesis may not keep pace with nitrogen fixation, thus making it impossible for the plant to build the fixed nitrogen into new tissue. Under such circumstances nitrogen compounds accumulate in the nodules, and if these are in contact with highly adsorptive surfaces or with the roots of other species, part of the excess nitrogen will be excreted as aspartic acid. As the development of the plant proceeds, the rate of photosynthesis may increase so as to stop excretion, and part of the excreted nitrogen may be readsorbed from the substrate. Bond and Boyes (2) have also advanced a hypothesis similar to this one. Numerous experiments have been made based on this hypothesis in which the environment was altered in order to change the relationship between photosynthesis and nitrogen fixation in inoculated leguminous plants. Three general methods have been employed to accomplish this, viz., through use of (a) shade; (b) the natural seasonal variation in light and temperature; and (c) artificial control of light and temperature. The positive results which were brought about by shading under certain conditions have been discussed by Wilson and Wyss (15). The findings of the other methods will be summarized in the two following sections.

Effect of season

In these experiments inoculated peas were seeded with oats or barley in the open clay pots; parallel runs were frequently included in which the "sterile" suction flask technique was employed. When this was done, the Finnish varieties of plants as well as strain of bacteria and type of sand were used routinely together with the local plants, bacteria, and sand. The quantitative aspects of the results have been discussed by Wilson (17); qualitatively the course of nitrogen excretion is illustrated in plate 2. Altogether more than two hundred plant cultures were included in these trials, but no excretion was observed in the great majority, although good fixation was often obtained. It was therefore concluded that excretion of nitrogen by the pea plant at the Wisconsin Experiment Station is definitely the exception rather than the rule. As is shown in plate 2, excretion was obtained with several cultures grown in the early fall months; other positive results were noted with plants grown during early spring. As the climate in both seasons is cool with a long day of moderately intense sunlight, the effect of these factors was further investigated.

Length of day and temperature

Cultures of peas (or vetch) with barley were grown in three greenhouses with the temperatures held at 90°, 70°, and 55°F. Each greenhouse was divided into two sections by a light-tight screen so that one section received only the normal

late winter illumination while the other section was supplied with supplementary lighting. In the high-temperature house the legumes failed to develop; at 70° F. only a small quantity of nitrogen was fixed, and no benefit from association was derived by the barley plants. In the low-temperature house distinct differences were evident between the plants grown under the normal short day and those receiving additional illumination. With both conditions the growth of the legumes was slow, but nitrogen fixation was relatively high, especially by the peas. Under the short day the barley made slow but extensive growth, extremely vegetative in character, and showed no signs of heading out at the end of the experiment. The barley in the association contained no more nitrogen than the controls. The control barleys grown under the long day grew as typical nitrogen-starved plants, naturing with heads containing only a few grains. Those in association showed a definite benefit and matured with large heads, as though supplied with a complete nutrient solution. The results are shown in plate 3, figure 1. The experiment, repeated in both glazed and unglazed pots, gave similar results.

In 1938 Dr. G. Bond, of the University of Glasgow, conducted similar experiments in conjunction with members of the research staff at the Wisconsin Experiment Station. Barley plants grown with peas in pit sand (glazed pots) at a low temperature with supplementary illumination showed definite evidence of benefit. Analysis of the sand showed that its nitrogen content also increased slightly; hence the observed benefit to the barley plants likely was due to the growth of the peas (17).

The results from the experiments shown in plate 3 emphasize, however, that mere use of this technique—growing the plants at low temperature and long day—will not insure the occurrence of excretion. In the experiment shown in figure 1 the growth of the peas was comparatively slow, and nitrogen fixation, although satisfactory, was not particularly noteworthy. In the experiment illustrated in figure 2 the peas grew extremely well, fixed unusually large quantities of nitrogen, but excreted none to the barley. These results are in good agreement with others we have observed over the past 5 years. Our positive results have most frequently been obtained with cultures in which the development of the legume was limited to a certain degree. When growth was unrestricted and fixation was unusually high, excretion was absent.

DISCUSSION

Extensive experiments made in the greenhouse and outside coldframes, in which hundreds of leguminous plant cultures kept under various conditions of growth were used, have resulted in only a relatively few instances of positive evidence of excretion. The more frequent occurrences of nitrogen excretion by legumes were noted when the experimental conditions included moderately low temperatures and light of comparatively low to medium intensity but of long duration. A survey of the regions in which positive excretion has been most consistently reported suggests that such environmental factors may have played a role.

Yet it is not to be concluded that light and temperature *per se* control excretion nor that the phenomenon occurs only under the conditions which favored it at our own station.   Rather, it apparently arises from an alteration of the plant's physiology brought about by a complex of interacting factors. This alteration results in the accumulation of an excess of soluble nitrogen compounds (with reference to available carbohydrate) in a specialized locale, the nodule, which permits outward diffusion into the substrate.   Such an extreme response of a plant to what may appear to be minor changes in the environment is not without parallel in botanical literature.   Murneek (8), Roberts and Struckmeyer (11), and others have reported examples in which a comparatively slight change in the temperature or insolation is accompanied by a marked alteration in the physiology or anatomy of the plant.

Studies on nitrogen excretion by legumes have yielded important additions to our knowledge of the biochemistry of the fixation process, but, except for isolated instances, the mass of experimental work has failed to furnish convincing evidence of the significance of the phenomenon in the agronomic practice of most agricultural regions.   Such proof admittedly is difficult to obtain because of the experimenter's lack of control over many factors in field trials.   There is, moreover, definite evidence that excretion does not occur even under specialized greenhouse environments when any approach to normal field conditions obtain, e.g., presence of combined nitrogen or poor aeration.   It is conceivable, nevertheless, that under the variable environment encountered by plants growing in the field, in some—perhaps short—period of growth the conditions favoring excretion will be met.   The view that since excretion is functionally possible it may be concerned with, but not the sole source of, the benefits of associated growth, does not appear unreasonable.   Ludwig and Allison (4), however, in summing up the evidence rightly emphasize that most of the present experimental data fail to justify even this modest conclusion.

The negative aspects of associated growth of legumes and nonlegumes have been, in our opinion, too often disregarded.   Virtanen ascribes the depressed growth of peas in association with a nonlegume when the ratio of legume to nonlegume is low to the robbing by the latter of much of the nitrogen which the leguminous companion has fixed.   Similar inhibition of the growth of legumes in association has been noted by others, including ourselves, often when no excretion of nitrogen has been demonstrable.   The deleterious effect of cereals upon legumes in India has been reported by both Madhok (6) and Raju.[3] Of great interest is the experience of Ahlgren and Aamodt [(1) and unpublished data] which strongly suggests that under certain conditions both components of a legume-grass association are inhibited.   For example, in both greenhouse and field experiments mixtures of white clover and bluegrass grew poorly on the same soil in which either species alone developed well.   Often one species would almost completely eliminate the other from the association.   The litera-

[3] Private communication [see (17)].

ture on field experiments is filled with examples of decreased yields due to association of unlike species (3, 5, 7). Until the factors governing the occurrence of the beneficial as well as the deleterious effects of associated cropping are better understood, we believe that sweeping recommendations for mixing of species are open to serious question.

SUMMARY AND CONCLUSIONS

Data and observations from extensive greenhouse experiments in which various legume-nonlegume associations have been used are discussed. The great majority of these experiments, which have covered a period of over 3 years, gave negative results as far as benefit to the nonlegume companion was concerned.

Certain environmental conditions, e.g., a long day and low temperature, produced by either natural or artificial means, appear to favor the occurrence of excretion at the Wisconsin station. The results in general, however, emphasize that no control of single factor or combination of specified factors (type of container, substrate, strain of organism, variety of plant, intensity of light, length of day) will ensure positive results. The view is advanced that all such factors exert their influence by reason of their collective alteration of the physiology of the legume. If the environmental conditions are such that the leguminous species fixes nitrogen at a rate in excess of its assimilation into new tissue, organic nitrogen accumulates in the nodule and is excreted as aspartic acid.

It is concluded that in order to bring about excretion it is necessary that the physiology of the plant be directed along a certain pathway. The best method for accomplishing this will probably vary in different regions. Moreover, a factor which is decisive in one locality may be without influence in another, or in the same locality at another time. To date, certain empirical procedures (temperature and day length) have been found to provide useful but not certain methods of inducing excretion in some leguminous species at the Wisconsin station.

The implications of these experiments and their interpretation for the agronomic practice of mixed cropping is considered, and certain limitations of associated cultures are indicated.

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PLATE 1

MIXED CROPPING OF SOYBEAN AND SUDAN GRASS

Pots 1, 3, and 5: Associated cultures; Pots 2 and 4: Controls—sudan grass alone. The benefit to the sudan grass in the associated cultures does not necessarily arise from excretion but may come from nitrogen leached from the soybean seed during germination. (See text for discussion.)

PLATE 1

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PLATE 2

Associated Culture of Peas with Cereals during Different Seasons

Upper left, experiment 13—August 22 to October 14, 1937; lower left, experiment 14—September 1 to October 14, 1937; upper right, experiment 21—October 8 to December 21, 1937; center right, experiment 24—October 20 to December 21, 1937; lower right, experiment 30—January 3 to April 5, 1938.

Peas have been removed for photographing development of nonlegume.   Control pots are left and third from left in experiment 13; center pots in all others.

Experiment 13—Left: Binder barley and Torstai peas.
                            Right: Wis. 38 barley and Canada field peas.
Experiment 14—Left: Guldregen oats and Canada field peas.
                            Right: Guldregen oats and Torstai peas.
Experiment 21—Left: Binder barley and Torstai peas.
                            Right: Guldregen oats and Torstai peas.
Experiment 24—Left: Wis. 38 barley and Canada field peas.
                            Right: Binder barley and Torstai peas.
Experiment 30—Left: Binder barley and Torstai peas.
                            Right: Wis. 38 barley and Canada field peas.

Rhizobium leguminosarum 317 used to iroculate Canada field peas; Finnish strain HX, Torstai peas.

PLATE 3

Fig. 1. Benefit to Barley of Growing in Association with Peas and Vetch in Long
Day and Low Temperature

Fig. 2. Absence of Benefit to Barley of Growing in Association with Peas in Long
Day, High Intensity, and Low Temperature

Left: Triplicate cultures of Binder barley and Torstai peas (HX bacterial inoculation).
Right: Control—Barley alone.

High intensity means that a 2000-watt lamp fitted with a water screen was used for supplementary illumination. Compare excellent growth of peas in this figure with those shown in figure 1 in which excretion was observed.

SOME EFFECTS OF SHEET EROSION ON SOIL MICROBIOLOGICAL ACTIVITY[1]

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The widespread phenomenon of soil erosion has been recognized in all its seriousness only in the last few years. By wind or water, surface soil is removed to be deposited elsewhere on the land or to be lost in drainage ditches and rivers. The effects of these soil movements on the microbiological population have received little attention. The activity of the soil population is controlled by three major interrelated factors, each of which may separately undergo change as a result of erosional processes. These factors are, first, the nature and number of organisms present; second, the amount and quality of the organic matter; and third, the physical environment. The flora of the different horizons of a profile is not identical either in number or type of organisms present. Similarly the organic matter as it decreases in amount with depth may also change in composition. Exposed layers, therefore, would not necessarily be expected to contain or to maintain a normal topsoil flora. Moreover, when movement of soil occurs as a result of water erosion, selective changes may occur in the inorganic and also the organic soil constituents, affecting the texture of the soil and thereby perhaps altering the physical environment of the soil population. These results of erosion cannot be completely disentangled.

HISTORICAL

There is little published information pertaining directly to the problem under investigation, although the literature on soil erosion, now very voluminous, does contain brief references to various aspects of the problem. Many publications have drawn attention to the great losses of soil, of plant nutrient elements, and of soil organic matter that occur, and to the fact that the exposed layers are in general less productive and lower in organic matter content. As a result of sheet erosion from slopes, soil may be deposited on more level areas below, but the material so deposited does not necessarily have the composition of the original surface soils. Bennett (1, pp. 111–116) reports analyses of sands deposited in the alluvial plain of Eighteen Mile Creek, South Carolina, by a destructive flood. The underlying soil had approximately 30 times as

much organic matter, 13 times as much nitrogen, and 16 times as much phosphoric acid as did recently deposited alluvium. According to Bennett, the finer particles may be removed to some extent from sandy soils subjected to rains of moderate intensity, leaving the larger, heavier particles behind, whereas clay soils and soils of granular or fragmental structure do not usually undergo textural changes, but instead the soil is cut away bodily by the run-off water.

Wind erosion is less widespread, but its effects on the nature and the flora of soils have been somewhat more extensively studied. Windblown dust may contain much less sand and much more silt than the original field soils (5). The effect of movement of soil by wind on the microbial flora has been investigated by Snow (10) in a number of windblown soils which, however, were not transported agricultural soils but desert or dune sands. She investigated the morphological and physiological forms present, made counts of fungi, bacteria, actinomycetes, and yeasts and in addition carried out certain chemical analyses.

A comparison of the microflora in the soil with that in the run-off has been made by Wilson and Shubert (15). Counts were made of bacteria and fungi by the plate method and of various physiological groups by the dilution method. The number of organisms in the run-off, expressed on the basis of dry solids, was on the average about 200 times greater than that in the surface soil from which the run-off was derived.

That the population of the soil layers exposed by erosion is likely to differ both qualitatively and quantitatively from that of the normal topsoil is evident. Many early investigators showed that the numbers of soil organisms decrease rapidly with depth, and more recently Brown and Benton (2) among others showed that the decrease with depth is related to the organic matter in the various horizons. Striking differences occur between the lower A and the upper B horizons. The maximum numbers of bacteria and actinomycetes generally were found in the A_1 or A_2 horizons, whereas the molds frequently reached a maximum somewhat deeper. Gray and associates (6, 7, 8, 9) in an investigation of Quebec podzol soils, have included studies of some of the more important groups of soil organisms and have attempted to assess the activity of the population by determining carbon dioxide production and nitrate liberation on incubation. The organic matter horizon of virgin podzol soils was shown to be biologically more active than the eluvial or illuvial horizons.

Purely quantitative studies of soil organisms have been recognized to be incomplete and sometimes misleading, and recently soil microbiologists have attempted primarily to obtain information about the activity of the population rather than its size as estimated from plate counts. As an example of this approach may be cited the work of Vandecaveye and associates (11, 12, 13) on the Palouse, Helmer, and Melbourne soils, in which they attempted to relate carbon dioxide evolution, bacterial numbers, and the distribution of certain fractions of the soil organic matter.

Description of soil samples

The soils used in these studies were collected in the fall of 1938 from cropped fields mostly in the southern part of Iowa. Each sample is a composite of at least five samplings.

Clinton samples. A group of Clinton silt loam samples from Johnson County, was used in most of these studies. The field had been in sod for the previous 6 or 7 years, but in 1938 it was plowed, planted to corn, and cultivated up and down the slope. All of the corn was at least 9 feet high, but that growing on the steepest slopes was slightly chlorotic and lacked sturdiness. Several severe storms had occurred during the summer, and serious erosion had taken place. The wash deposits at the bottom of the slope were of considerable depth, at least an inch of which was deposited only a week before the samples were collected. The samples were taken as follows:

1. Uneroded surface soil from top of hill, 0–3 inches, slope 1 per cent.
2. Remainder of the A horizon at the same site, 3–6 or 3–7 inches.
3. Top 3 inches of the B_1 horizon of the same site, 6–9 or 7–10 inches.
4. Eroded soil 50 yards down slope from site 1, mixture of A and B_1, 0–4 or 0–5 inches, slope 10 per cent.
5. Next 3 inches of B_1 horizon, 4–7 or 5–8 inches.
6. Severely eroded soil 70 yards down slope from number 1, mixture of A and B_1, primarily B_1, 0–3 inches, slope 12 per cent. In places all the loessial material had been removed, exposing the till.
7. Wash material deposited in 1938, 30 yards down slope from sample 6, 0–2 or 0–4 inches.
8. Wash material deposited about 10 yards down slope from number 7, 0–3 inches.

Additional composite samples were taken of only the surface soil at approximately the same locations the following spring (April 27, 1939) and used solely for bacterial counts.

Marshall silt loam samples. Samples of Marshall silt loam to a depth of 6 inches were taken from the center of a timothy pasture in Audubon County, as follows:

12. Uneroded surface sample of the smooth upland from an area of 1 acre, east of channel in which wash had been deposited.
13. Eroded slope sample slightly east of north of center of the quarter.
14. Wash deposited a short distance to the east of the center of the quarter.

Clinton silt loam, Lindley loam samples were collected at the Hillculture Experiment Station near Floris, in Davis County, Iowa. All samples, except those of wash deposits, were taken to a depth of 3 inches. The samples were as follows:

18. Uneroded Clinton silt loam, slope 2 per cent or less, from area which had received an application of 2½ tons of lime and 300 pounds of 2–12–6 fertilizer per acre in the spring of 1938. Part of the area was fallow, part in alfalfa, and the rest in weeds.

19. Eroded slope, mixture of A and B horizon of Lindley loam, 300 feet southeast of sample 18, slope 13 per cent, fertilizer treatment as for sample 18, vegetation consisting mainly of weeds.   This portion of the field had been contoured 3 months before.
20. Wash deposits from areas sampled for 18 and 19, primarily from 19, deposited in 1938, slope 2 per cent or less, fertilizer treatment and vegetation same as for sample 19.
21. Eroded slope, mixture of A and B horizons, predominantly B, of Lindley loam, sampled 200 feet north of sample 18, slope 22 per cent, upper part of area had received same fertilizer applications as sample 18, lower portion had not been fertilized, vegetative cover consisted of weeds.
22. Wash eroded from areas sampled for 18 and 21, primarily from 21, slope 3 per cent or less, no vegetation and no fertilizer treatment.

Shelby silt loam samples were collected in a corn field in Lucas County which for several years previously had been in sod.   In 1937 and 1938 the area was planted to corn.

27. Eroded slope, mixture of A and B, but primarily B, slope 13 per cent.
28. Wash material from area sampled for 27.

Determinations

The following determinations were carried out:

Carbon by dry combustion (A.O.A.C. method).
Nitrogen (Gunning-Hibbard modifications of the Kjeldahl method).
Inorganic nitrogen (ammonia and nitrate together) by distillation of a KCl extract of soil with dilute alkali in the presence of Devarda's alloy.
Hydrogen-ion concentration by glass electrode.
Total exchange capacity by the ammonium acetate method of Chapman and Kelley (3).
Total exchangeable bases by the titration method of Williams (14).
Bacterial counts using 5 plates per dilution on Thornton's agar incubated at 25°.
Distribution of organisms by the Cholodny slide procedure as described by Conn (4).
Carbon dioxide evolution in incubation tests.   Since the number of samples studied was large, a method other than those involving constant aeration was required.   The CO_2 evolution from 100 gm. soil passing a 10-mesh sieve was determined, both alone and with the addition of organic matter, such as cornstalks.   Such material was ground to pass a 20-mesh sieve and was previously heated to 85° for 24 hours to destroy the greater proportion of the organisms present.   Sufficient water was added to each soil to bring the moisture content up to 60 per cent of the approximate moisture-holding capacity, as determined by the Hilgard method, plus 3 ml. of water for each gram of organic matter.   The soils were incubated in closed quart milk bottles, the CO_2 evolved being absorbed in 0.5 N NaOH contained in a short wide test tube resting on the soil.   For the first 6 days of the incubation, titrations were made daily, and thereafter every 2 days for a total period of 2 weeks.   At the time of each titration the air was blown into the bottles in order to ensure a sufficiency of oxygen.

Chemical changes due to erosion

Total nitrogen, total carbon, inorganic nitrogen, and pH were determined on each soil, and in addition the total exchange capacity and exchangeable bases on the Clinton samples from Johnson County.

Clinton samples (table 1).   The surface soil from the most severely eroded part of the slope (sample 6) contained less carbon and nitrogen than the wash

(samples 7 and 8), the less severely eroded slope (sample 4), or the uneroded surface soil (sample 1). The total carbon and nitrogen were lower in the wash

TABLE 1

Chemical analyses of Clinton samples

Expressed on oven-dry basis

SAMPLE NUMBER	TOTAL CARBON	TOTAL NITROGEN	C/N RATIO	TOTAL EXCHANGE CAPACITY	TOTAL EXCHANGE-ABLE BASES	AMMONIA + NITRATE N	pH
	per cent	*per cent*		*m.e.**	*m.e.**	*mgm.**	
1	1.60	0.157	10.2	14.1	12.8	1.98	5.34
2	1.61	0.145	11.1	14.8	13.2	0.77	5.55
3	0.71	0.074	9.5	15.8	15.4	0.68	5.85
4	1.04	0.107	9.8	18.4	16.7	0.71	5.74
5	0.40	0.045	9.0	16.8	17.2	0.44	6.54
6	0.83	0.076	11.0	15.0	13.4	0.40	5.28
7	0.95	0.087	10.9	13.8	13.4	1.09	5.40
8	0.99	0.100	9.9	13.1	12.6	2.27	5.61

* Per 100 gm.

TABLE 2

Chemical analyses of Marshall, Clinton-Lindley, and Shelby samples

Expressed on oven-dry basis

SAMPLE NUMBER	TOTAL CARBON	TOTAL NITROGEN	C/N RATIO	AMMONIA + NITRATE N	pH
	per cent	*per cent*		*mgm.**	
Marshall samples					
12	2.17	0.197	11.0	†	5.15
13	2.34	0.197	11.9	†	5.38
14	1.84	0.170	10.9	†	5.60
Clinton-Lindley samples					
18	2.03	0.172	11.8	2.97	5.83
19	0.57	0.057	10.1	0.99	5.97
20	0.21	0.022	10.0	0.53	6.38
21	0.64	0.061	10.6	0.53	5.07
22	0.25	0.024	10.3	0.26	5.18
Shelby samples					
27	1.24	0.119	10.4	1.51	5.01
28	1.62	0.134	12.1	2.10	6.98

* Per 100 gm.
† Not determined.

than in the average of the surface soils above. The rapid decrease in carbon and nitrogen in the slope samples can be explained by the profile distribution

of organic matter in a gray-brown podzolic soil. The subsurface samples had a higher degree of base saturation and were less acid than is usual in a typical Clinton soil.

Marshall samples (table 2). The differences among the samples of the Marshall soils were not so great as those among the Clinton samples. The slope sample had slightly more carbon and the same amount of nitrogen as the uneroded sample. The pH was highest in the wash sample and lowest in the uneroded sample.

Clinton-Lindley samples. The soil samples from the Hillculture Experiment Station were from a field in which the erosion had been very severe. The uneroded sample had almost four times as much carbon and nitrogen as the slope sample, and almost ten times as much as the wash sample. Since part of the field had not been limed, wash sample 22 and slope sample 21 had appreciably lower pH values than the others.

Shelby samples. The eroded Shelby slope (sample 27) had a lower quantity of total carbon and of total nitrogen and a lower pH than the deposited wash (sample 28). .

Bacterial studies

Plate counts. Numerous investigators have attempted to use counts of bacteria, fungi, or actinomycetes and of various physiological groups of organisms as indicative of the relative fertility levels of soil. It is recognized that only a fraction of the total population will develop on agar plates, and that numbers may not be a satisfactory index of potential activity. Total counts of bacteria by the plate method were made in the Clinton soil (table 3). The counts could not be made immediately after sampling; instead, on the following day, the composite samples were placed, without being dried, in auto-irrigator pots and held at constant moisture for 16 days in order that the increased development of the population that immediately follows sampling and mixing should not seriously alter the results. The samples collected the following spring were plated on the same day as sampled. Despite the many inaccuracies of the plate method, the differences between samples were great, and it was apparent that the surface soils of the eroded slope did not contain so large a population by this measure as did the uneroded topsoil or the wash. The wash, much of which was recently deposited when the first samples were taken, did contain a considerable number of organisms, and in the following spring gave by far the largest count, doubtless as a result of a change in availability of the organic matter caused by abrasion during transport.

Cholodny slides. In an endeavor to determine possible differences in the nature of the flora, and in particular the types of organisms present and active in the wash, the Cholodny slide technic was employed on the Clinton soils. Slides were buried in all composite samples and also in undisturbed surface samples taken in glass crystallizing dishes. Though the results obtained by

examination of these slides cannot be easily summarized in tabular form, certain features were clearly apparent. In the first place, actinomycetes were much more prevalent in all samples than is commonly observed in most cultivated soils. They were especially abundant in the surface soils (samples 1, 4, 6, 8), doubtless because the field had been in sod for several years prior to 1938. Fungi were present on most of the slides examined and were abundant in one of the undisturbed wash samples. After incubation for 22 days the composite samples of slope and wash materials had in general a larger bacterial and a smaller actinomycete population than earlier. The wash samples did not appear to differ particularly from the samples taken on the slopes above, whether in numbers, types, or distribution of organisms present, even though the wash was newly deposited.

TABLE 3

Numbers of bacteria in Clinton samples

Millions per gram on oven-dry basis*

SAMPLE NUMBER	FALL 1938	SPRING 1939
1	11.1	9.4
2	5.1	†
3	3.5	†
4	5.0	11.6
5	2.6	†
6	2.9	6.4
7	7.1	13.5
8	†	26.6

* Numbers determined by plate method.
† Not plated.

Microbial activity studies

The evolution of CO_2 may properly be used as a measure of the activity of the soil population. Activity is not a single value but a composite of the behavior of the organisms present on the substrate available under the physical environmental conditions that prevail. The "ventilation" method commonly employed in the measurement of CO_2 evolution from soils and decomposing materials has obvious disadvantages if many samples have to be run at the same time, since a separate absorption apparatus, either tower or Pettenkoffer tube, must be used for each sample and the adjustment of many slow uniform air-streams always presents difficulties. Since the CO_2 evolution figures are ordinarily employed for comparative purposes, and not as absolute values like total carbon or nitrogen, the "simultaneous absorption" method with its greater simplicity is preferable. As the method was employed in these experiments, the oxygen supply was never limiting. Identical results should not necessarily be expected when "ventilation" and "simultaneous absorption"

methods are compared, because the oxygen concentration is not constant in the closed vessel, and because the absorption in the latter method is not quantitative under all conditions but only within certain limits of time and CO_2 concentration. A comparison of the CO_2 collected in 14 days by the two methods from duplicate samples of the surface uneroded Clinton soil (sample 1), alone and after the addition of 1 per cent cornstalks or alfalfa, showed that the cumulative totals differed in about the same proportion, the absorption method giving about 80 per cent of that obtained with continuous aeration (table 4).

The evolution of CO_2 from the soil on incubation has frequently been used to obtain information on the condition of the organic matter of the soil. It is asserted, however, that differences in the size and nature of the microbial population can be detected by differences in the rate of decomposition of added plant material, provided no factor limiting activity is operative. The rate of

TABLE 4

Evolution of carbon dioxide from uneroded Clinton topsoil, as determined by the "ventilation" *and "simultaneous absorption" methods*

On basis of 100 gm. air-dry soil with and without addition of 1 gm. plant material

TREATMENT	METHOD	TIME	CO₂ EVOLVED		S/V
		days	*mgm.*	*mgm.*	
None..............	Ventilation (V)	14	152.7	140.7	
None..............	Simult. absorp. (S)	14	118.2	125.5	0.83
Cornstalks.........	Ventilation (V)	14	673.0	711.3	
Cornstalks.........	Simult. absorp. (S)	14	615.8	603.7	0.88
Alfalfa............	Ventilation (V)	7	737.8	715.1	
Alfalfa............	Simult. absorp. (S)	7	599.0	603.4	0.83

decomposition is measured in terms of the major end product, namely CO_2, and expressed as milligrams per hour between sampling times. This method and its implications will be discussed in more detail in another publication.

The cumulative CO_2 evolution in 14 days from the soils, both with and without the addition of 1 gm. cornstalks (43.4 per cent C; 1.26 per cent N; C/N = 34/1) to 100 gm. soil, is shown in table 5, and the rates of evolution are shown in figures 1, 2, and 3. Some further information as to the condition of the soil organic matter was obtained by incubation of the soils without cornstalk additions for a further period of 2 weeks, the inorganic nitrogen (NO_3-N + NH_3-N) liberated then being determined.

Clinton samples. When incubated alone, the most CO_2 was evolved from the uneroded topsoil in the surface (0–3-inch) and immediate subsurface (3–6-inch) layers. Where erosion had been most severe (sample 6) only about half as much CO_2 was evolved but, even so, the amount was greater than that produced by the 6–9-inch layer of the uneroded area (sample 3) or the 3–6-inch

layer part way down the slope (sample 5). In CO_2 evolution, the deposited wash samples fell between the most severely eroded slopes and the moderately eroded slope samples. Except in the case of sample 5, which contained the smallest amount of organic matter, the percentage of the soil carbon appearing

TABLE 5

Evolution of carbon dioxide and mineralization of nitrogen on incubation of samples

On basis of 100 gm. air-dry soil with and without addition of 1 gm. cornstalks

SAMPLE NUMBER	CO_2 FROM SOIL ALONE	TOTAL C OXIDIZED	CO_2 FROM SOIL AND CORNSTALKS	AMMONIA + NITRATE N LIBERATED	TOTAL N MINERALIZED
	*mgm.**	*per cent*	*mgm.**	*mgm.†*	*per cent*
Clinton samples					
1	122	2.1	610	3.32	2.1
2	122	2.1	575	4.32	3.0
3	49	1.9	378	1.32	1.8
4	82	2.1	492	2.74	2.6
5	41	2.8	364	1.20	2.7
6	62	2.0	426	5.13	6.8
7	74	2.1	555	2.49	2.9
8	79	2.2	582	2.97	3.0
Marshall samples					
12	101	1.3	537	‡	‡
13	111	1.3	616	‡	‡
14	63	0.9	623	‡	‡
Clinton-Lindley samples					
18	130	1.7	637	3.38	2.0
19	65	3.0	524	1.44	2.6
20	50	5.9	428	1.33	6.2
21	59	2.5	386	0.64	1.0
22	41	4.2	374	0.80	3.3
Shelby samples					
27	99	2.2	482	2.06	1.7
28	89	1.5	664	3.65	2.7

* Incubation period 14 days.

† Incubation period 30 days.

‡ Not determined.

as CO_2 was almost identical. There was no evidence in this series that the organic matter exposed by erosion or deposited in the wash was any less or any more oxidizable than that present in the uneroded topsoil.

After the addition of cornstalks the CO_2 evolution for the soils was increased in very different degrees. It is not legitimate to subtract from the totals that

evolved from the soils when incubated alone, though it will be recognized that the soil organic matter as well as the added cornstalks may contribute to the total. The amount of carbon added was 434 mgm., which, if it were fully utilized, would give rise to 1591 mgm. CO_2. In the slope samples, surface and subsurface, the amount oxidized during the incubation was distinctly less than that in the uneroded surface or wash samples. The activity of the population in the wash, which, because of its mode of formation and newness, might have been expected to be biologically unbalanced, was high and was little inferior to that of the uneroded surface soil.

Additional information is provided by plotting the rate of evolution per hour determined at daily intervals (fig. 1). When incubated alone, the maximum rate of evolution was reached in the first day, then falling more or less rapidly until about the eighth day, after which it became more nearly constant. The rate of evolution from the 0–3- and 3–6-inch layers of the uneroded topsoil was identical and considerably higher than that from any of the slope samples or from the 6–9-inch sample taken at the same place. When cornstalk additions were made, a different picture was obtained. Greater differences were apparent not merely in rate, but also in the time elapsing before the maximum rate was reached, the latter being of particular significance. In the case of the eroded samples and the subsurface uneroded samples, the maximum rate was not reached until the second day of incubation, whereas the surface uneroded samples and the wash samples reached a maximum on the first day. Of these the initial activity was greatest in the deposited wash (samples 7 and 8), indicating that this material contained a large and active flora. The differences in behavior of the uneroded samples, 1, 2, and 3, may be interpreted as follows: Samples 1 and 2 possessed much the same population, a deduction based on the observation that from the fourth day onward the rates of evolution were almost identical. The number of organisms present, however, was greater in the surface sample, maximum activity in which was reached the first day, whereas in sample 2 some time elapsed before the population attained full activity. In the 6–9-inch layer (sample 3) the initial peak, attained on the second day, was considerably lower, and throughout the whole experiment the rate of evolution was about one-third less than that from the layers above. In shape and magnitude this curve is similar to that for the most severely eroded sample (sample 6).

The amounts of nitrogen mineralized in the incubation period of 30 days varied more widely than the carbon oxidized. The surface sample from the eroded slope (sample 6), though almost the lowest in total nitrogen content, contained the highest amount of inorganic nitrogen. There was an indication that the nitrogen of the organic matter in the wash samples was slightly more readily mineralized than that of normal surface soil, perhaps as a result of mechanical effects of transportation.

Clinton-Lindley samples. The results on the Clinton-Lindley soils are of especial interest, inasmuch as most of the samples were from severely eroded
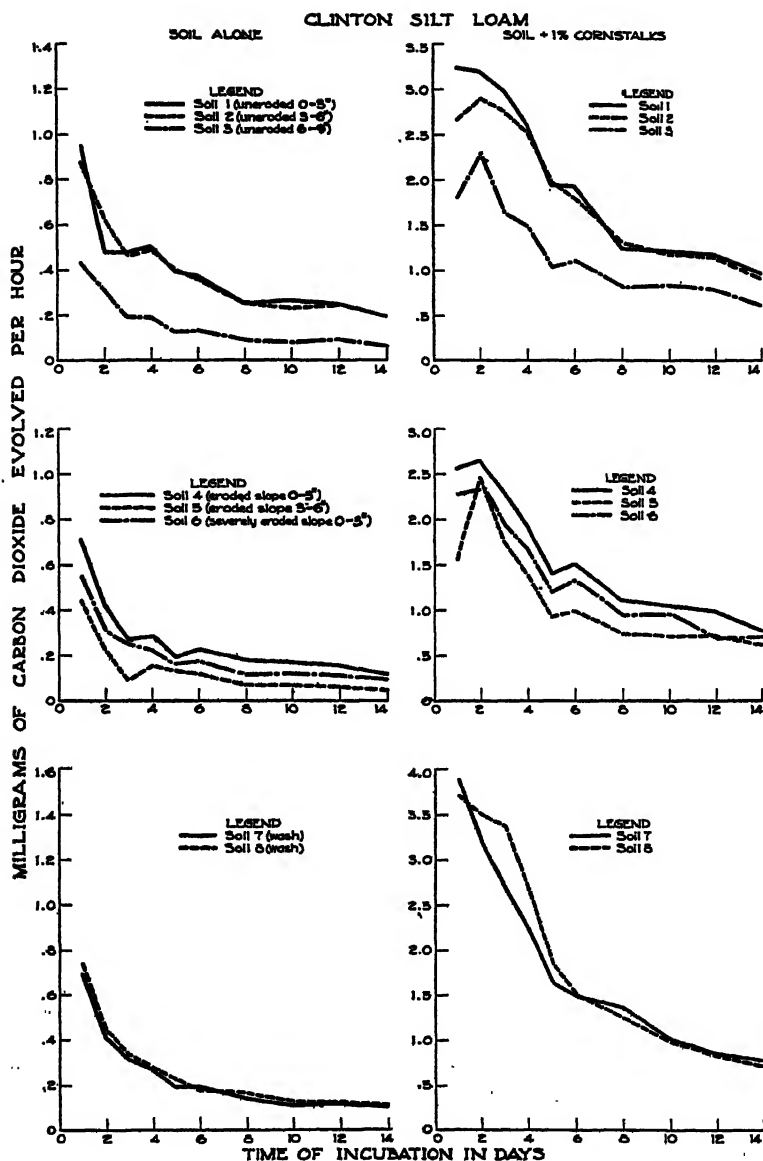
FIG. 1. RATE OF EVOLUTION OF CARBON DIOXIDE FROM CLINTON SAMPLES WITH AND WITHOUT ADDITION OF CORNSTALKS

areas as evidenced by the low organic matter contents. On incubation alone the amount of CO_2 evolved (table 5) was small except from the relatively un-eroded upland sample, 18. The proportion of the carbon oxidized in the wash

(samples 20 and 22) was distinctly higher than that from the other samples, and the same tendency also was apparent in the nitrification figures, where again, though the amounts liberated were small, they represented a higher percentage of the total nitrogen present than obtained from other samples. After addition of the cornstalks, substantial differences were apparent. Samples 18, 19, and
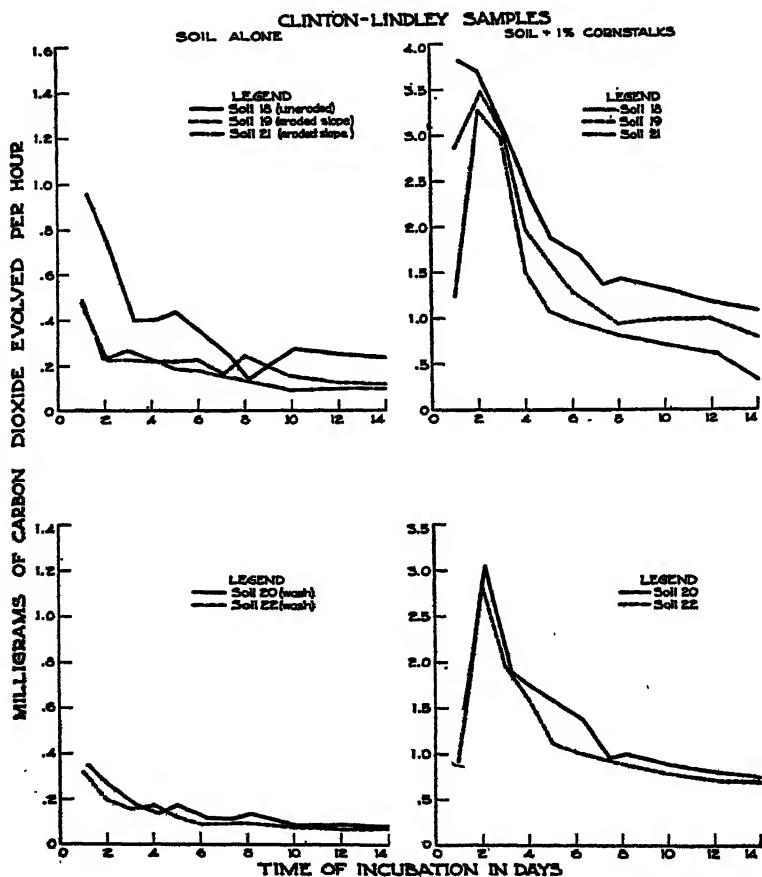
FIG. 2. RATE OF EVOLUTION OF CARBON DIOXIDE FROM CLINTON-LINDLEY SAMPLES WITH AND WITHOUT ADDITION OF CORNSTALKS

20 were from a limed area, and 21 and 22, from an unlimed area, and the effects of the treatment appear both in the total CO_2 evolved and in the nitrogen mineralized, in accordance with the findings of Gray (7) and others.

The rates of evolution of CO_2 from the slope samples of soil alone were not dissimilar to those from the wash (fig. 2). When cornstalks were added, however, differences were apparent. The peak evolution from the upland surface soil (sample 18) occurred on the first day, whereas from both slope

samples the maximum was not reached until the second day, the rate of liberation from the limed sample on the first day being more than twice as great as
that from the unlimed.   These results can be interpreted as indicating both
qualitative and quantitative differences in the population present.   The
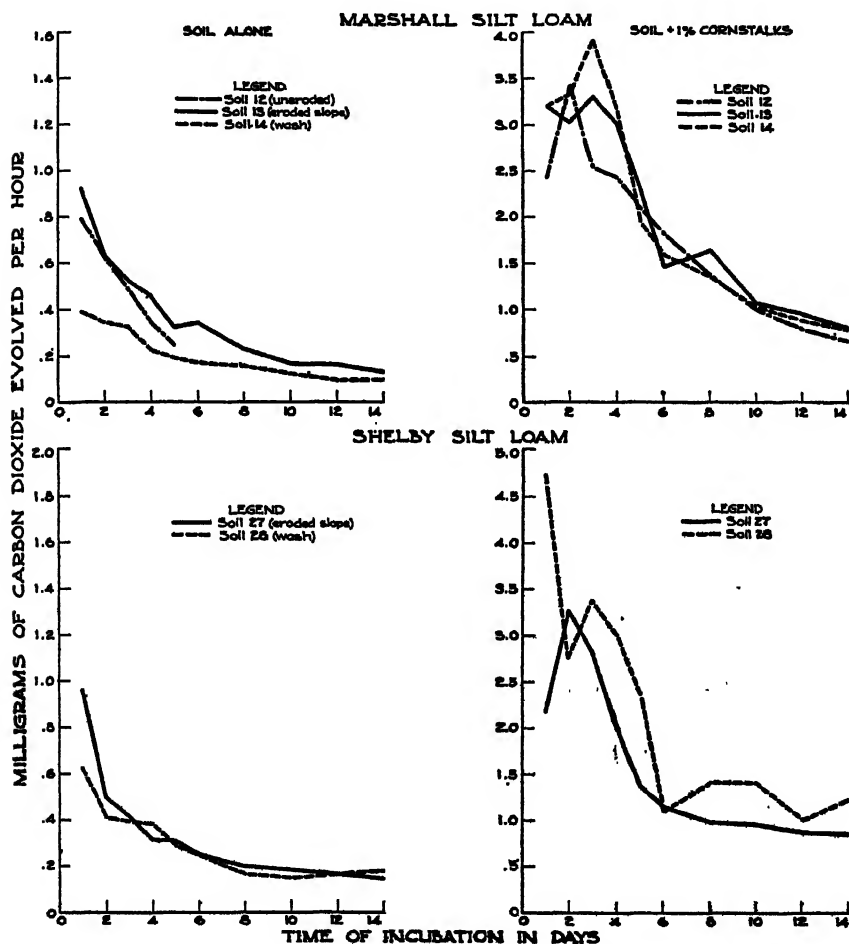
FIG. 3. RATE OF EVOLUTION OF CARBON DIOXIDE FROM MARSHALL AND SHELBY SAMPLES
WITH AND WITHOUT ADDITION OF CORNSTALKS

uneroded soil evidently had a larger and more active population than the
slope or wash samples and as a result brought about more rapid and more
extensive decomposition of the added material. Even after the first week,
when the initial burst of activity had subsided, the rate of evolution from these
samples remained significantly different.

Marshall samples. Though the Marshall samples were higher in organic matter than the Clinton samples or the Clinton-Lindley samples, the CO_2 evolved was of much the same order, the percentage of carbon oxidized from the Marshall being lower, showing that the organic matter is more resistant. Particularly was this the case in the wash (sample 14), in which less than 1 per cent of the carbon was oxidized in 14 days. On the addition of cornstalks, however, the amounts evolved were relatively high, indicating an active population. The rates of evolution from soil with cornstalks were somewhat erratic and not markedly different (fig. 3). The highest peak was obtained from the wash on the third day, and the eroded slope did not seem to be biologically inferior to the topsoil. This is perhaps understandable in a praire soil, such as the Marshall, in which the organic matter falls only slowly with depth.

Shelby samples. More CO_2 was evolved from the slope (sample 27) than from the wash (sample 28) on incubation, even though the latter had the higher carbon content. Mineralization of nitrogen, however, was in the reverse order, despite a wider C/N ratio in the wash. In this sample again it would seem that one of the effects of transport is an increase in the availability of the soil nitrogen. On addition of cornstalks the wash sample yielded appreciably more CO_2, the peak of evolution occurring on the first day (fig. 3). The maximum rate in the slope sample was not reached until the second day, and the subsequent level of activity was not so high.

DISCUSSION

The study of the soil population has passed through several phases, and it is now generally accepted that the potential activity of the population cannot be simply assessed by any one of the usual bacteriological techniques, and that qualitative comparisons of the population of different soils are extremely difficult and unsatisfactory. In attempts to study the effects of erosion on the population, additional complications arise. These, as cited earlier, are the simultaneous effects on the soil organic matter upon which the population is maintained, and the effects on texture which may change the physical environment of the population. It is impossible completely to separate these interrelated factors and perhaps of little importance to attempt to do so. The practical question that inevitably arises is whether eroded soils and deposited wash contain normal or abnormal floras and whether, if organic matter is incorporated, decomposition will proceed normally through the usual sequence of transformations.

The principle of "additions" has been employed in these studies for the evaluation of the potential activities of the soil population. The use of a plant material not too plentifully supplied with soluble constituents, and high enough in nitrogen so that the available nitrogen level of the soil in which it was incorporated would not be limiting, does permit of a quantitative estimate of the activity of the population, though it provides no information as to the nature of the differences. The cumulative total and the relative rates of

evolution of CO_2 are indexes of the efficiency of the population in decomposition, and the time elapsing before the rate reaches its maximum may be a measure of the number of active organisms in the soil.

Permanent changes in the soil population as a result of erosion are probably closely related to changes in the amount and nature of the soil organic matter. In most agricultural soils the carbon and nitrogen content decreases continuously with depth, and consequently as erosion removes the surface layers the quantity of these constituents in the exposed soil becomes less. The chemical and physical nature and the availability to microorganisms of this organic matter are not necessarily the same as those in the original surface horizon. This is also true of the organic matter in the wash deposits which, as a result of erosional processes, may have been fractionated and abraded and its availability thus changed by exposure of new surfaces to microbial activities.

From the studies reported, it would seem that the surface soil of eroded slopes does not contain a flora so large or potentially so active or effective in the decomposition of added organic matter as the normal topsoil flora of the uneroded soil of the same general area. The deposited wash, however, may be biologically very active, with the result that decomposition processes within it may be as rapid as in uneroded topsoil.

SUMMARY

Sheet erosion might be expected to affect the activity of the soil flora by changing the nature and number of the organisms present, the amount and quality of the organic matter, and the physical environment. Samples of uneroded topsoil, eroded slopes, and deposited wash from related areas have been examined to obtain information as to the effect of sheet erosion on the population.

Erosion had the effect of reducing the organic matter content of the exposed slopes, but the amount in the deposited wash varied with the site and soil type. On incubation, the slope and wash samples evolved less CO_2 than the uneroded upland topsoil, the amount in general being proportional to the organic matter content. The percentage of the carbon oxidized in the Clinton samples was almost identical, but in other series there was evidence of a greater availability of the organic matter in the wash.

The CO_2 evolved after the addition of 1 per cent cornstalks was considered as indicative of the potential activity of the populations. Wide differences in the rate of evolution and in the total evolution in 14 days were found in the various soils, the eroded samples in most cases giving substantially less CO_2 than the uneroded topsoils. Moreover, from eroded slope and subsurface samples the maximum rates were not attained until the second or third day, indicating the presence of a smaller and less active population than in the uneroded surface samples, the peak evolution from which invariably occurred on the first day. Most wash samples contained an active population and gave a peak on the first or second day.

The population of the exposed surface soil of eroded slopes is quantitatively smaller than that of the uneroded upland topsoil, and it is also qualitatively inferior in the decomposition of added organic matter. Deposited wash, however, may be biologically active.

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DIFFERENCES IN THE AGGREGATION OF A PRAIRIE AND A GRAY-BROWN PODZOLIC SOIL[1]

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Structure is recognized as having both direct and indirect effects upon the soil as a plant habitat. Directly, it affects root penetration, soil aeration, and the intake and conservation of soil moisture; indirectly, it affects soil fertility by influencing biological and chemical reactions. One of the methods of measuring soil structure is to determine the number and size distribution of water-stable aggregates.

The results of aggregation studies on two genetically different soils are reported here. The effect of cultivation on structure was determined by comparing the aggregation results from cultivated and from virgin fields of each of the two soils. Three different kinds of organic matter were added to composite soil samples from the cultivated fields of each of the two soils, and the effects on aggregation were noted. The effect of time on the degree of aggregation resulting from these organic matter additions was also determined. A method of expressing aggregation and aggregate size distribution as a single number is presented.

LITERATURE REVIEW

Many materials have been studied for their effect on the promotion of aggregation. The beneficial effects of organic matter have been pointed out by Browning (6), Baver (2), and Kubiena (10); but Rogers (15) and Bradfield (4) have reported instances in which the beneficial effects of this material were questioned. Gel'tser (8) and Peele (13) recently directed attention to the part played by the secretions of organisms on the formation of structure, and Kanivetz and Pritzker (9) have implied similar results from their investigations.

Bouyoucos (3), Rhoades (14), Cole and Edlefsen (7), and Yoder (18) have proposed methods of measuring the aggregation of soils. All the methods are empirical, and care in operation is needed to obtain reproducible results. The Yoder method was used in this study.

The lower size limit of a beneficial aggregate has not been agreed upon. Russell (16) reports the choice of several investigators in this respect. Baver and Rhoades (1), Lutz (11), and others have used a lower aggregate size limit of 0.05 mm. Browning (6) used 0.25 mm. as a lower size.

MATERIALS AND EXPERIMENTAL PROCEDURE

The samples used in the following studies were taken in Lucas County, Iowa, in November 1939. Albia silt loam[3], a prairie soil, has developed from loess under a grass vegetation. A virgin profile has a very dark brown, almost black, loosely granular surface horizon. Weller silt loam, a gray-brown pod-zolic soil, has developed from identical parent materials and under similar environmental conditions except that oak-hickory timber, instead of grass, was the vegetative cover. The Weller soil has a grayish-brown color and a fine, soft granular structure in the surface horizon. On the sites sampled the slopes ranged from 2 to 5 per cent.

Ten sites, 5 on Albia silt loam and 5 on Weller silt loam, were located and sampled. Each selected site consisted of an adjacent cultivated and a virgin part, each of which was sampled five times. Thus, from each site 10 samples were taken giving a total of 25 virgin and 25 cultivated samples for each of the two soils. Additional larger samples taken from the cultivated spots were later combined into composite samples for further studies. The samples were broken from the side of a hole with a spade, and portions crushed or coming in contact with the spade were discarded. In both the cultivated and the virgin areas the samples were taken to a depth of 6 inches. On occasion, the virgin Weller samples were taken to depths of 3 or 4 inches to avoid sampling the bleached A_2 horizon. Each of the 10 sampled spots in each site was taken at irregular intervals in a more or less linear fashion along the contours of the slope. The average distance between sampling spots was about 57 feet. The sites were carefully selected[4] and are believed to represent well the two soils as mapped in Lucas County.

Observation and local inquiry at the time of sampling indicated that none of the virgin sites had been cultivated for a great number of years, whereas some of the cultivated sites had been cultivated for as much as 60 years.

In the laboratory the samples were put through a quarter-inch square-hole wire sieve. As some of the cultivated field samples were dry and lumpy force was required to screen them; the virgin samples screened readily. The samples were then air dried and stored. Previous to aggregate analysis all samples used in this study were placed in a humidor and allowed to reach a moisture equilibrium with air maintained at 50 per cent relative humidity by sulfuric

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[3] "Albia silt loam" is a tentative name used in the soil survey of Lucas County and is subject to change in the final correlation of that area.

[4] The sites were selected by J. R. Johnston, of the U. S. Soil Conservation Service, who was a member of the soil survey party working in Lucas County at that time.

acid.   This required 4 to 8 days.   Aggregate analyses were made by the Yoder (18) method.

Two composite samples were made by combining the cultivated samples from the five sites of each soil after they had previously been screened and air dried.   The air-dry Weller and Albia samples contained 1.53 and 2.56 per cent of moisture, respectively.   The moisture equivalent was 18.40 and 21.53 per cent respectively for the Weller and Albia samples.   Organic matter in the form of finely chopped cornstalks and alfalfa was added to portions of the two composite samples at the rate of 50 tons an acre.   Another set of samples received sucrose at the rate of 47.6 tons an acre, thus giving equivalent carbon contents to all samples.   After the soil and organic materials had been dry mixed in a drum-shaped rotary mixer, 210 gm. of each soil-organic matter mixture was placed in each of six quart mason jars and sufficient water was added to obtain the moisture equivalent percentage.   Sucrose and ammonium-nitrate were added on solution to one series of jars at the rate of 4.76 and 0.173 gm. per 100 gm. of soil, giving a carbon-nitrogen ratio of about 33/1.   The nitrogen content of the alfalfa was 2.1 per cent, and that of the cornstalks was 0.96 per cent.   The jars were buried up to the necks in sand in the green-house to prevent excessive evaporation, the lids were set—not screwed—on the jar tops, and the moisture percentage was maintained throughout the period by frequent additions of distilled water.   At the end of 30, 84, and 168 days, two jars of each treatment were removed and the contents dried.   Later the air-dry soil was passed through a sieve having 0.312-inch openings.   Before the aggregate analyses were made, the sieved soils were placed in a humidor as previously described.

Total carbon was determined on the untreated field samples by the dry combustion method as described by Winters and Smith (17).   Mechanical analyses were made by the pipette method of Olmstead, Alexander, and Middleton (12).   Total exchange capacity was determined by the ammonium acetate method.   Total exchangeable bases were determined by the method of Bray and Willhite (5).

Most investigators who have expressed aggregate analysis data as a single number have used the percentage of the total sample weight that is composed of aggregates above a certain arbitrarily chosen size.   Such a method ignores the distribution of the aggregates above or below this size.

It is well known that the total surface area of a given weight of soil increases as the particle or aggregate size is reduced.   Therefore, the total surface area per unit weight can be used as an index of dispersion.   The results of this investigation are reported in terms of a single figure called the *coefficient of aggregation.*   This figure is proportional to the reciprocal of the total surface area per unit weight of soil.   Those soils having the largest coefficient of aggregation are best aggregated.

In calculating the coefficient of aggregation the following assumptions are made: aggregates of all sizes have the same average density; aggregates of

all sizes have the same average configuration; and the diameters of the aggregates on any given screen are linearly distributed between the diameter of the openings of that screen and the opening of the next larger screen. On the basis of these assumptions the weight of aggregates on each sieve is proportional to the third power of the average diameter of the aggregates. Therefore, the weight divided by the average diameter gives a number proportional to the surface area of the aggregates. The coefficient of aggregation was calculated as 10^6 times the reciprocal of the sum of the $\left(\dfrac{\text{weight}}{\text{ave. diameter}}\right)$ values for the aggregates of each size group. The average diameters used for the aggregates of the different group sizes in this investigation are as follows:

SCREEN SIZE	AVERAGE DIAMETER
mm.	*cm.*
>5.0	.600
5.0 to 2.0	.35
2.0 to 1.0	.15
1.0 to 0.5	.075
0.5 to 0.25	.0375
0.25 to 0.10	.0175
<0.10	.005

RESULTS AND DISCUSSION

Field samples

In addition to the aggregation studies made on all the field samples, the soils from two sites were selected for additional studies, in order to check on any differences which might have been present. Composite samples were made from the virgin and from the cultivated parts of the soils from site 6 and from site 9. The results of these studies are given in table 1.

The Albia has a greater total exchange capacity than the Weller. Cultivation decreased the exchange capacity of both soils. Both virgin soils contain nearly the same amounts of exchangeable bases, but in the cultivated soils the exchangeable bases of the Albia have increased whereas those of the Weller have decreased with respect to the original percentage of saturation. The increase in exchangeable bases accompanied by the increase in pH suggests that lime had probably been applied to the sampled area of cultivated Albia. The Weller soil contains considerably smaller amounts of exchangeable hydrogen and has a higher pH than does the Albia soil. The mechanical analyses of the two soils showed that the chief differences occur in the fraction $<2\mu$, the Albia soil having a larger amount of clay than the Weller soil.

Aggregate determinations were made in duplicate on the 100 samples. The results are expressed in terms of the coefficient of aggregation. Figure 1 shows that large differences occur between the virgin and the cultivated soils for both the Albia and the Weller, but the differences between sites of the same soil type are greater than the differences between the two soils.

The coefficient of aggregation of the cultivated Weller was 49 per cent that of the virgin Weller, whereas, in the Albia soil, the coefficient of aggregation of the cultivated samples was 57 per cent of the corresponding virgin samples. Some of the reduction in aggregation accompanying cultivation of the Weller soil may be attributed to the incorporation of the bleached A_2 horizon into the sampled zone by tillage operations. The coefficient of aggregation of the virgin Albia was 16 per cent less than that of the virgin Weller. This is indicated in figure 2 by the greater percentage of Weller aggregates larger than 0.5 mm. as compared to the Albia. The coefficient of aggregation of the cultivated Albia was 2 per cent less than that of the cultivated Weller. This close agreement is

TABLE 1

Some chemical and physical properties of the Albia and Weller soils

Averages of duplicate determinations

	ALBIA		WELLER	
	Virgin	Cultivated	Virgin	Cultivated
Total exchange capacity*.........	23.0	21.7	15.3	12.7
Total exchangeable bases*........	13.5	17.6	13.1	10.2
Exchangeable hydrogen†.........	8.5	4.3	2.2	2.5
pH‡.............................	5.14	5.51	5.58	5.41
Mechanical analyses				
Solution loss§................	4.42	4.53	1.95	3.86
Sand > 300 mesh.............	3.78	3.84	4.89	4.23
< 300 > 5μ...................	60.6	65.5	73.7	71.1
< 5μ........................	28.7	29.6	21.2	23.1
< 5μ > 2μ...................	5.80	6.47	7.64	8.54
< 2μ........................	22.9	23.1	13.8	14.6

  * Results in m.e. per 100 gm. soil.
  † By difference.
  ‡ Glass electrode determinations.
  § Includes organic matter loss. Results in percentage.

also delineated in figure 2 where the aggregate distribution of these two soils is shown to be very similar.

The summation of all the aggregate distribution data, as shown in figure 2, reveals that about 50 per cent of the aggregates for both cultivated soils are smaller than 0.10 mm., whereas only about 22 per cent of the aggregates of the virgin soils have diameters less than 0.10 mm. The close similarity of the aggregate size distribution of the cultivated soils indicates that cultivation has tended to obliterate any differences which existed between the aggregation of these two soils in the virgin state.

An analysis of variance of the coefficient of aggregation revealed that the differences between sites within the soil types and between the cultivated and the virgin samples were highly significant. The differences between the two soils were adjudged significant when compared with the experimental error.

Since highly significant differences occurred between the sites within the soil types the mean square of the soils should, however, be compared with the mean square of the sites within the soils. Such a comparison revealed the soils to be not significantly different. The great variability within the soil types emphasizes the need for adequate sampling.

Additional analyses of variance determined on the cultivated and the virgin samples separately indicated that, independent of previous cultural practices, the aggregations of the Albia and Weller soils do not differ significantly but that highly significant differences exist between the different sites within each soil type.
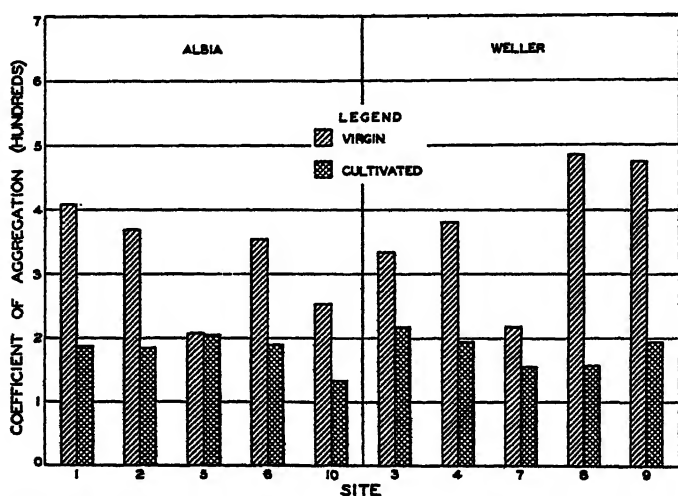
FIG. 1. COEFFICIENTS OF AGGREGATION OF VIRGIN AND OF CULTIVATED SAMPLES FROM FIVE SITES EACH OF THE ALBIA AND WELLER SOILS

The total carbon content of the different-sized aggregates was determined on samples from three sites each of the Weller and Albia soils. Figure 3 summarizes the results of these determinations for all the aggregate sizes except for those remaining on the 5-mm. sieve. The material on this sieve in many instances contained large amounts of roots and other undecomposed organic materials, but in some instances, not enough soil remained on this screen to make the carbon determination.

In figure 3, three points of interest are evident: first, the Albia soils contain more total carbon than do the Weller soils; second, the cultivated soils have a lower carbon content than do the virgin soils; third, the smaller aggregates tend to contain the least amounts of carbon. From the last of these, it might be concluded that by increasing the organic matter content of the soil, larger and more stable aggregates would be formed. On this assumption the order
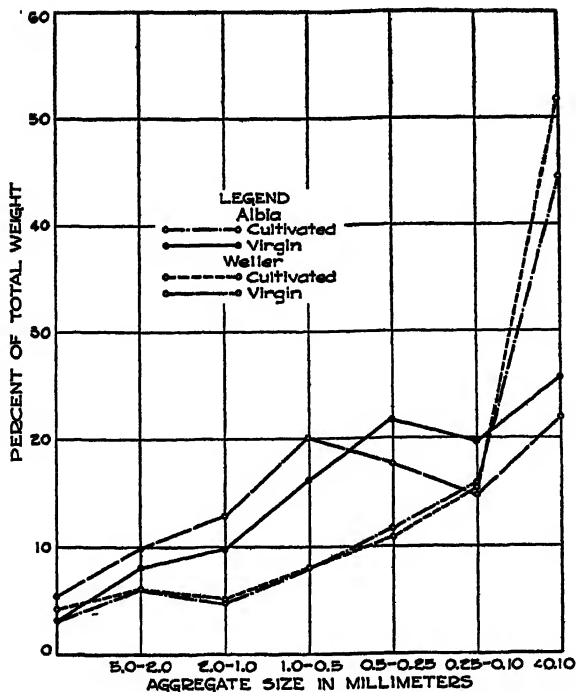
FIG. 2. AGGREGATE SIZE DISTRIBUTIONS FOR VIRGIN AND CULTIVATED SAMPLES OF THE ALBIA AND WELLER SOILS

Average of all samples
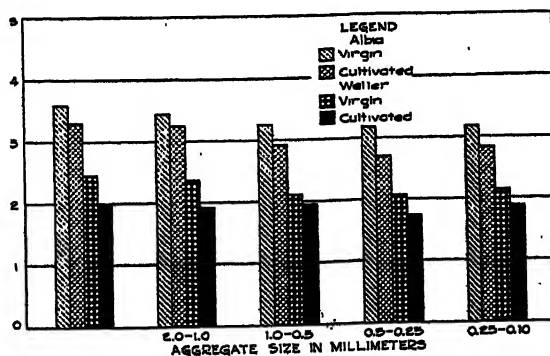
FIG. 3. TOTAL CARBON CONTENT IN AGGREGATES OF FIVE SIZES FROM CULTIVATED AND VIRGIN SAMPLES OF THE ALBIA AND WELLER SOILS

of best to poorest aggregation should be virgin Albia, cultivated Albia, virgin Weller, and cultivated Weller, whereas, as previously shown, the actual order

of best to poorest aggregation was virgin Weller, virgin Albia, cultivated Weller, and cultivated Albia. From these results it may be concluded that the percentage of total carbon present bore no direct relationship to the degree of aggregation of the two soils studied.

Clay is often considered to be a cementing agent which binds individual soil grains into aggregates. To determine the possible effects clay may have had on the aggregation of the soils studied, mechanical analyses of aggregates of four sizes were made on material composited from the several samples taken

TABLE 2

Mechanical analysis of aggregates of different sizes from virgin and cultivated Albia and Weller soils

Results in percentages

	AGGREGATE SIZE	SOLN. LOSS*	SAND	$\leq 50\mu$ $> 5\mu$	$< 5\mu$	$\leq 5\mu$ $> 2\mu$	$< 2\mu$
	mm.						
Albia Virgin	5.0 to 2.0	5.15	3.36	59.6	28.0	6.84	21.1
	2.0 to 1.0	4.68	3.87	60.9	30.2	7.06	23.1
	0.5 to 0.25	5.02	3.36	60.2	31.0	6.34	24.7
	0.25 to 0.1	4.87	3.41	60.8	32.0	7.12	24.7
Cultivated	5.0 to 2.0	5.19	6.67	59.3	31.2	5.54	26.7
	2.0 to 1.0	4.49	7.26	55.1	31.5	4.69	26.8
	0.5 to 0.25	4.17	7.22	52.7	32.9	5.29	27.5
	0.25 to 0.1	4.21	3.60	55.7	35.9	5.77	30.2
Weller Virgin	5.0 to 2.0	3.40	2.76	67.2	26.6	9.62	17.3
	2.0 to 1.0	3.09	3.04	66.5	26.2	9.54	16.6
	0.5 to 0.25	2.87	4.65	61.5	25.9	8.79	17.2
	0.25 to 0.1	4.12	3.09	68.4	26.7	9.81	16.9
Cultivated	5.0 to 2.0	2.33	5.50	64.0	27.0	7.68	19.2
	2.0 to 1.0	2.12	7.74	61.6	27.8	8.09	18.9
	0.5 to 0.25	2.15	8.46	81.8	28.2	9.55	18.7
	0.25 to 0.1	2.33	4.60	66.2	29.2	8.44	20.7

* Includes solution and organic matter loss.

in both cultivated and virgin areas at site 6 (Albia) and site 9 (Weller). The results are given in percentages in table 2.

A study of the table reveals no marked differences in the distribution of any mechanical analysis fraction in any of the different aggregate sizes for either the virgin or cultivated parts of the Albia and Weller soils. A considerable difference is noted between the two soils in the $<2\mu$ fraction of all aggregate sizes, which, if the clay content is important in aggregation, would result in a better aggregation for the Albia soils than for the Weller soils. It has been pointed out that the virgin and cultivated Weller soils are better aggregated than the corresponding Albia soils. From table 2 it is also apparent that the

$<2\mu$ fraction has been increased slightly by cultivation and yet, as noted previously, cultivation has markedly decreased the aggregation of both soils. These results would indicate that there is neither a direct nor a consistent indirect relationship between aggregation and the percentage of clay in the two soils studied.

Treated samples

As previously explained, two composite samples, one of Weller and one of Albia, were made of soil from each of the sampled spots from the cultivated parts of all the field sites. Treatments and procedures have been explained. The three treatments (sucrose, alfalfa, and cornstalks) produced a similar degree of aggregation on each of the two soils; the relative effectiveness of the
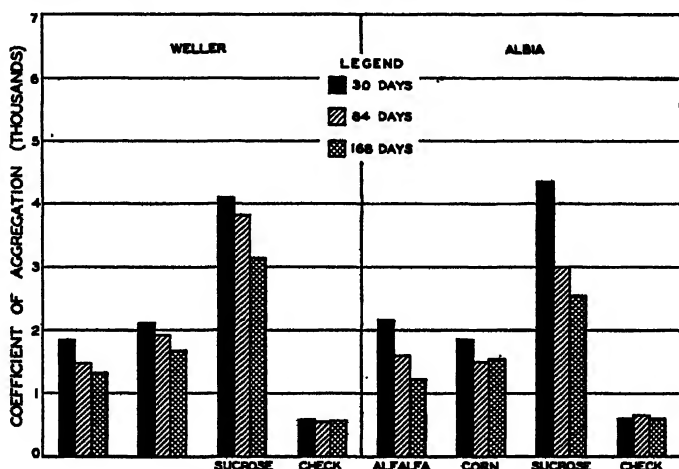
Fig. 4. COEFFICIENTS OF AGGREGATION OF ORGANIC-MATTER TREATED SAMPLES OF THE ALBIA AND WELLER SOILS AT THREE SAMPLING DATES

treatments was maintained throughout all three sampling periods. The different treatments, however, gave marked differences in aggregation. The effectiveness of each treatment in promoting aggregation decreased with increasing periods of time as shown in figure 4. At the 30-day sampling date the coefficients of aggregation for sucrose, cornstalks, and alfalfa were, respectively, 720, 335, and 335 per cent of the coefficients of aggregation of the check; at the 84-day sampling period these percentages had decreased to 575, 290, and 260, respectively; and at the 168-day period the corresponding percentages were 487, 274, and 212. In the order of their decreasing value in promoting aggregation, the treatments were, therefore, sucrose, cornstalks, and alfalfa.

The percentage of total weight of the different aggregate sizes for the entire period according to the treatment received is shown in figure 5. In both soils the addition of sucrose resulted in the formation of a greater percentage of

aggregates >0.5 mm. than did either the alfalfa or cornstalk additions. The cornstalks and alfalfa gave closely similar aggregate distributions. All of the treatments for each of the sampling periods increased the aggregation of both
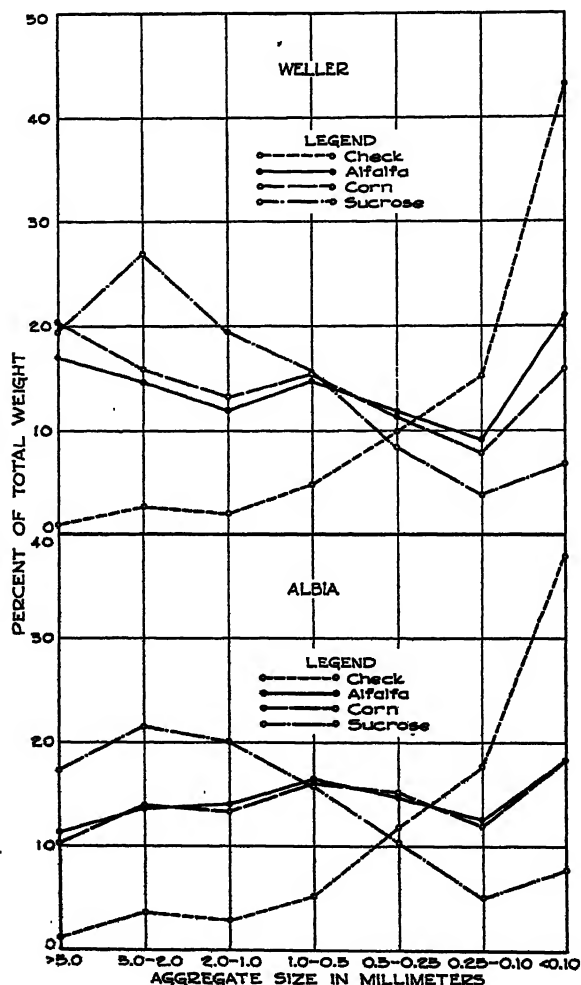
FIG. 5. AGGREGATE SIZE DISTRIBUTIONS OF ORGANIC-MATTER TREATED SAMPLES OF THE ALBIA AND WELLER SOILS

Average of the three sampling periods

soils over that of the corresponding check. The sucrose treatment was the most effective in producing large aggregates at each sampling date.

An analysis of variance of the data obtained from this part of the investigation revealed that there was no significant difference between the coefficients

of aggregation of the two soils but that the differences between the treatments and between the three sampling dates were highly significant. The significance of the soil $\times$ treatment and the treatment $\times$ date interactions was traced to the variations of the check values. When the analysis was repeated without the check as one of the treatments there were no significant interactions. The highly significant difference existing between the treatments is caused by the much better aggregation in the samples treated with sucrose as contrasted with those treated with cornstalks and alfalfa. The latter two treatments were not significantly different in their effect upon the aggregation of either the Albia or the Weller soil, although all treatments caused highly significant increases in aggregation over the untreated samples.

From these results it is apparent that the formation of water-stable aggregates is greatly aided by the additions of organic materials to these soils. In all cases the best aggregation results were obtained from the 30-day sampling period, indicating that the formation of water-stable aggregates was greatest sometime before the second sampling period. The great superiority of sucrose over either alfalfa or cornstalks in promoting aggregation is to be noted. From this it is apparent that a large percentage of the aggregation of soils is due not to the organic matter added but perhaps to the mucus and slime secreted by the organism using the organic materials as a food source.

SUMMARY AND CONCLUSIONS

Aggregation studies have been made on two soils developed from identical parent materials but under different types of vegetation. Ten samples were taken from each of five sites of Albia silt loam, a prairie soil, and from five sites of Weller silt loam, a gray-brown podzolic soil. At each site half of the samples were taken from virgin areas and the remainder from adjacent cultivated areas. Aggregation was measured by the Yoder method, and the results were expressed in the form of a single number called "the coefficient of aggregation."

Highly significant differences in aggregation were found between the several sites within each soil type. The variability within the soil type obliterated any differences that may exist between the two soils and emphasized the need for extensive sampling in aggregation studies. Cultivation resulted in highly significant decreases of 88 and 65 per cent respectively in the coefficients of aggregation of the Albia and Weller soils. Mechanical analyses and total carbon determinations revealed no simple relationship between the degree of aggregation and the percentage of total carbon or of $<2\,\mu$ clay in either of the soils studied.

Greenhouse studies on composite samples from cultivated areas of the Albia and Weller soils revealed that the two soils were not significantly different in their aggregation response to large organic matter additions. Thirty days after the addition of equal amounts of carbon in the form of sucrose, cornstalks, and alfalfa at the rate of 50 tons of dry matter per acre the coefficients

of aggregation of the two soils had increased to 720, 335, and 335 per cent respectively of the untreated check. Each of these percentages decreased progressively at the 84- and 168-day sampling periods.

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SOIL REACTION AND VARIETAL ADAPTATION OF WHEAT

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In a previous paper (4) we showed that wheat varieties differ in their adaptation to soil reaction. The conclusions were based on the fact that in both pot and field soils of different pH values the relative yields of certain varieties compared to those of some other varieties increased when pH increased. But the alkaline soils were, in general, richer than the neutral or acid soils; and the differences in adaptation to soil reaction might be attributed to differences in adaptation to soil fertility. In order to elucidate this question, we have carried out many experiments since 1937–38.

EXPERIMENTAL PROCEDURE

The first year, we established a scale of pH values by adding to samples of the same soil different amounts of H_2SO_4 or NaOH. The results, with respect to varietal adaptation, though not significant, were in agreement with those of our paper of 1935 (4); but they might be attributed to some changes in organic nitrogen mobilization and in the availability of calcium, phosphorus, and iron, caused by addition of the NaOH or H_2SO_4.

The second year, we used a method analogous to that described below, except that the solution contained small quantities of soil for buffering and did not contain $NaNO_3$. The results were in agreement with those of the preceding year, but root growth was very poor in a solution containing no nutrients.

The experiments of both years indicated that only the higher pH values are injurious and that only to these did the wheat varieties show differences in adaptation. For this reason, we confined our experiment of 1939–40 to the higher pH values.

In 1939–40 we adopted the following procedure: Wheat plants of two varieties, one tolerant of alkaline soil (Mentana) and the other, of acid soil (Eretria), were sown on November 20 in very small containers (8 cm. in diameter by 6 cm. in depth) with perforated bottoms. Each pot contained 200 gm. of dry soil fertilized with 0.1 gm. of 20 per cent superphosphate. Beneath these pots were placed glasses containing 2700 cc. of a 0.1 per cent $NaNO_3$ solution, which, in turn, contained different quantities of NaOH, as follows: 0.05, 0.02, 0.01, 0.0033, 0.002, 0.00133, 0.001, 0.0005, 0.00028, 0.0002, 0.0001, and 0 gram molecules per liter. There were five pots per variety for each

quantity of NaOH. The solution was renewed every 6 days. Many determinations, which were made as late as April, showed that the pH of the solution was not appreciably modified at 6-day intervals.

By this method, most of the indirect influences of the solution reaction, like those on organic nitrogen mobilization and on calcium, phosphorus, and iron availability, were suppressed. The only indirect influences not thus suppressed were that of the Na ion and that on nitrate absorption, and these may be considered as direct, because they are always associated with soil alkalinity. Moreover, as the researches of Clark and Shive (1, 2) and of Davidson and Shive (3) have shown, soil alkalinity decreases the rate of absorption of nitrate nitrogen. Since the alkali-tolerant variety Mentana is better adapted to an abundance of nitrogen (5), this influence tends rather to depress than to enhance this tolerance. In consequence, this influence cannot lead us to erroneous conclusions.

EXPERIMENTAL RESULTS

In this solution containing relatively large quantities of NaOH (0.05, 0.02, and 0.01 gram molecules per liter), the roots were very small and unhealthy; in fact, many of them died and were replaced by new roots. This observation is in agreement with that of Sideris (6) in respect to pineapples, except that on pineapples the ill effects of alkalinity were observed at pH 7–7.5, whereas on wheat they appeared at a much higher pH. Another difference is that Sideris used water cultures, and for this reason did not exclude the possibility that the bad effects were due to the precipitation of phosphorus, calcium, and iron ions. Our experimental procedure, on the other hand, precludes such an explanation. The injury was more serious for the acid-tolerant variety Eretria than for the alkali-tolerant variety Mentana. The pH values, of course, were higher than those encountered in usual alkaline soils, but the same alkalinity is much more harmful in a buffered environment than in a nonbuffered one.

The mean grain yields, in grams per pot, were as follows:

NaOH, GRAM MOLECULES PER LITER	MENTANA	ERETRIA
0.05, 0.02, 0.01	0.219 ±0.05	0.036 ±0.05
0.0033, 0.0020, 0.00133	0.331 ±0.05	0.237 ±0.05
0.001, 0.0005, 0.00028	0.413 ±0.05	0.442 ±0.05
0.00002, 0.0001, 0	0.400 ±0.05	0.498 ±0.05

From these figures, it is evident that with the larger quantities of NaOH the yield of the alkali-tolerant variety Mentana was six times as great as that of the acid-tolerant Eretria and that with the smaller quantities of NaOH Eretria yielded 25 per cent more than Mentana.

SUMMARY

Two wheat varieties, one tolerant of acid and the other of alkali, were grown in solutions containing 0.1 per cent $NaNO_3$ and different quantities of NaOH. The nutrients other than the nitrate were supplied by the soil of small containers, with perforated bottoms, in which the plants were sown. It was observed that in the more alkaline solutions the roots, especially of the acid-tolerant variety, were small and unhealthy. Many of them died and were replaced by other roots. The alkali-tolerant variety gave a yield six times as high as that of the acid-tolerant variety in the more alkaline solutions, whereas the acid-tolerant variety gave a yield 25 per cent higher than that of the alkali-tolerant variety in the less alkaline solutions.

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LEAF ANALYSIS AND PLANT NUTRITION

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The methods of studying plant nutrition described in this paper were developed as a guide to the fertilizing policy of a large rubber-producing company. The company's estates are situated on some half dozen major soil types with numerous intermediate and local variations. The soil position is further complicated by varying degrees of past cultivation and erosion. From the outset it was decided to supplement the standard methods elaborated by soil chemists in the temperate regions with those developed by plant physiologists. The latter will mainly be considered here.

An extensive fertilizing and replanting program had been undertaken by the company, and it was essential to acquire, with the minimum of delay, the data necessary to advise on the conduct of this work. None of the methods in use in Malaya at that time were suitable for studying the nutritional requirements of rubber under these conditions. With a long-term crop like rubber. field experiments would have taken years to mature and were obviously too slow if unsupported by laboratory data. On the other hand, soil analysis as a means of determining nutrient requirements was known to have failed in the hands of previous Malayan workers. Furthermore, although there were abundant indications of phosphate deficiency, the combination of phosphate with nitrogen in many instances gave a smaller latex yield increase than did the application of nitrogen alone. The vital processes of the plant, growth rate[2] and latex production, were therefore followed by frequent measurements, and the correlation between these and leaf composition was studied. The method has proved surprisingly useful not only for the study of rubber, but for plants occupying very different systematic positions.

Leaf analysis was also of value in elucidating certain phases in the ecology of the leguminous covers which were being grown in association with the rubber.

[2] Throughout this paper where growth rate is referred to in connection with seedling rubber, increase in height has been used as the standard; in mature rubber, increase in girth has been used as the standard.

More recently, this technique has been used to investigate the nutrition of the oil palm (*Elaeis guineensis*). The same general principles are applicable and the method is proving equally valuable, but the very different structure of the plant necessitates considerable modification in detail. This work will not be considered here.

The evidence suggests that the methods described in this paper may be applicable to a rather wide range of problems in plant nutrition. It is from this point of view that data obtained mainly from work on *Hevea brasiliensis* is presented to readers not specifically interested in any of the plants studied. Details of purely local interest will therefore be excluded as far as possible.

A review of work on the fertilizing of rubber prior to 1936 has been given by Haines and Guest (9) and this early work calls for no further comment except an observation made by Grantham (7). This worker observed that rubber fertilized with nitrogen and phosphate yielded less latex than rubber fertilized with nitrogen alone. This is the first recorded observation on rubber, of the interaction between nitrogen and phosphate which has proved so important in the present investigation.

Haines (10) has recently noted a negative interaction between potash and nitrogen with phosphate. He observed that potash reduced growth rate of young rubber and this delayed the time when the trees first become tappable. This is the second important interaction considered below.

Dyck (6) has published the analysis of an entire rubber tree together with certain generalizations which appear to be only partly applicable to rubber. But leaf composition has not been used as a guide to nutritional status.

Gregory (8) has summarized recent work on certain aspects of plant nutrition dealing mainly, as does the present paper, with the three elements N, P, and K. Grain yield in barley is shown to be closely correlated with the supply of these nutrients. When nitrogen is lacking, yield is proportional to the nitrogen absorbed, according to Liebig's law of minimum. But when potash is deficient, the curve showing potash absorbed against yield is of the Mitscherlich type. In the work on rubber, potash deficiency has rarely been encountered, and no example of the Mitscherlich type of curve has been obtained. There is evidence, however, that rubber may be peculiar in this respect, since oil palms appear to give the typical Mitscherlich relationship with potash.

The deficiency of a single nutrient may sometimes alter the absorptive capacity of the plant for various other nutrients. This is well illustrated by the findings of workers on iron-deficiency chlorosis.

Several workers (3, 5, 18) report that the ratio of sodium and potassium to calcium in leaf ash is often greatly increased by iron-deficiency chlorosis. There never seems to have been any doubt that these changes in ash composition were due to changes in plant metabolism induced by lack of available iron. More recently Rohde (15) has again discussed the hypothesis put forward by the writer (3) that these phenomena may be related to one another through the oxygen metabolism of the plant. With nitrogen, phosphorus, and potas-

sium, when the addition of one nutrient to the soil leads to a change in rate of absorption of the others, it is often more difficult to determine whether this is due to a change in the soil or the plant or both. Blenkinsop (2) has investigated the effect of various substances on the availability of plant nutrients in the soil as judged by their water solubility. He found that potassium salts and sulfur depress phosphate solubility whereas ammonium sulfate increases it. These results are closely paralleled by the changes in ash composition of rubber plants following the application of these substances. This aspect of the problem will not be further considered here.

The importance of balance in nutrient supply has often been emphasized. McDonald (12) and Thomas and Mack (16, 17) also found that balance in the leaf was important, but in the present work any balance in the fertilizer mixture was important. The results obtained from the fertilizer mixtures undoubtedly depended largely on reactions within the soil proceeding quite independently of the plant.

In rubber leaves the absolute quantities of the nutrients and not their ratios are important within the range of compositions studied here. Too much emphasis should not be placed on this difference in the results, because in unpublished work on the oil palm the writer has obtained results of both types according to the degree of nutritional deficiency existing in the plants.

Thomas and Mack also found that the composition of a plant species changes during development. This has also been shown by other investigators whose work has been summarized by Gregory. A similar change takes place in rubber. It will be noticed on comparing the analysis for leaves from young and old rubber that the leaves of the latter are much poorer than those of the former in N and P. In rubber the change, however, is spread over years and is more particularly associated with the change in the type of spur produced by the tree at maturity. Spurs of limited growth normally carry smaller leaves lower in nutrients than do those of indefinite growth. Except in very young trees, both types of spur are often present together, and as pointed out below, sampling must be restricted to one type if comparable results are to be obtained.

Although rubber does not appear to differ fundamentally from the plants studied by other workers, these differences in detail necessitate a somewhat different approach to the study of its nutrition.

SAMPLING METHODS

It will be shown later that leaf composition is dependent on age, leaf type, and the time of the day. For comparative work, sampling must therefore be restricted to leaves of the same type and age and all samples should be taken between sunrise (6 a.m.) and 10:30 a.m.

During the first year of life a normal rubber tree has only one shoot, which elongates about every 5 weeks. During more than 3 weeks in each period the plant is resting, no fresh leaves are formed, and the increase in height is in-

appreciable. With each fresh growth a new whorl of leaves is produced. These leaves are large at the bottom and small at the top of the whorl. The largest leaf at the base of the uppermost mature whorl was always sampled. It is shown below that this leaf contains the highest percentage of N, P, and K of any mature leaf on the plant. Since the growth cycles of most young rubber plants in a field are coincident, it was usually possible to sample at a time when 90 per cent of the plants were dormant. This time was chosen because nutrients are withdrawn most rapidly from the mature leaves when new growth is taking place. In old rubber there are often two types of shoots present, spurs of limited growth corresponding to the fruiting spurs on the apple tree and spurs of unlimited growth. The former are more numerous, and the leaves from them were exclusively used in this work. Each growth spur carries a single whorl with the larger leaves at the base, as in young rubber. In sampling leaves from an old rubber tree the largest leaf was taken from each of two well-developed whorls high up in the light and on opposite sides of the tree. This work was carried out by gangs of coolies who were directed from the ground when cutting spurs. The leaves were finally selected from these spurs.

Normally rubber in Malaya winters during February and March, but certain trees winter whenever there is a drought, and in some districts where the rainfall is abnormal there are two winterings per annum. On trees wintering normally, the young leaves attain their maximum percentage content of N, P, and K soon after attaining maturity, and little change takes place until June unless secondary wintering sets in, when all three nutrients are returned to the tree in considerable quantities. Wintering trees, therefore, were never sampled in comparative work, nor was old rubber normally sampled between the first of November and the last of March.

ANALYTICAL METHODS

All leaves were collected in the morning and dried the same day. Drying was carried out as rapidly as possible in electric ovens just above 100°C. and lasted about 20 minutes. If the green color was not fully retained the samples were discarded, as it was shown that nitrogen was lost.

The midribs of the leaves were removed by hand after drying, and the leaves were then ground in a coffee mill adapted for a mechanical drive. The resulting leaf powder was sieved twice through a 40-mesh screen. This treatment was found to give a fair separation of the mechanical tissue from the softer tissues of the leaf, which were more easily pulverized in the mill. The mechanical tissue was considerably lower in nitrogen than the rest of the leaf and was rejected on the grounds that the composition of the active metabolic regions of the leaf should give the best indication of nutritional status. After being ground, the leaf powder was again dried before it was sampled for the nitrogen determination by Pregl's micromethod (14, pp. 109–114). The powder was ashed in stainless steel milk dishes at scarcely red heat. For the determination of phosphate and potash, approximately 0.015 gm. of the ash sample was

brought into solution in a Pyrex test tube with a mixture of 50 per cent H_2SO_4 (2 drops) and strong HCl (4 drops) first on the water bath and later in a hot-air bath maintained just below the boiling point of sulfuric acid. It was found that all the potash dissolved readily, but low results were obtained for phosphate unless the hot-air bath was used. The solution was made up to 5 cc., of which 2 cc. were taken for the potash determination and 0.5 cc. for the phosphate.

Phosphate was determined colorimetrically by the molybdate blue method. The iron contained in the ash was insufficient to interfere if sodium meta-bisulfite was added before the stannous chloride.

Potash was determined by a modification of the method described by Lewis and Marmoy (11). By this modification (4) it is possible for a man to carry out 10 potash estimations per hour when an assistant has prepared the ash solution. Previous to the last year the method described by Milne (13) was used but was too slow for regular routine work with the labor available. Only after the new method had been evolved could nitrogen, phosphorus, and potash be determined on every leaf sample.

It should be emphasized that in practice the success of the technique outlined below depends primarily on the rapidity with which the nutrients studied can be determined analytically. It is now universally recognized that biological work of this type must be highly replicated and susceptible of statistical analysis. In the present investigation it has been necessary to carry out, on rubber leaves alone, more than ten thousand chemical determinations mostly of nitrogen, phosphorus, and potassium. Statistical examination showed that the accuracy obtainable with rapid micromethods was more than sufficient for this type of investigation. The standard deviation for individual plot growth rates and latex yields was rarely below 10 per cent, whereas the standard deviation for a chemical determination as calculated from a representative sample of 60 chemical determinations, each carried out in duplicate, was 0.90 per cent of the respective elements present.

FACTORS INFLUENCING LEAF COMPOSITION

The composition of mature leaves from different places on the stem of year-old seedlings was determined. Seedlings that had 5 whorls of leaves were selected for experiment. Whorl 1 was in course of formation, and the leaves of whorl 5 were beginning to show occasional senescent color changes. Only leaves which did not show these color changes were sampled. The following generalizations from the data collected may be made. In each mature whorl, N and P contents are related to leaf weight, and when leaves of the same weight in different whorls are considered, there is a fairly regular drop in N and P percentages from whorl 2 to whorl 5. Although potash diminishes with whorl age, only in whorl 2 is it related to leaf size. In whorl 1, leaf weight and composition are not closely related because the leaves are in very different stages of maturity and during leaf formation composition changes rapidly with age.

In whorl 5 the senescent changes have produced very large decreases in all three nutrients.

The relations between N in dry leaf, N and P in leaf ash, and fresh leaf weight were found to be logarithmic. The relation between potash content of leaf ash and leaf weight was somewhat erratic.
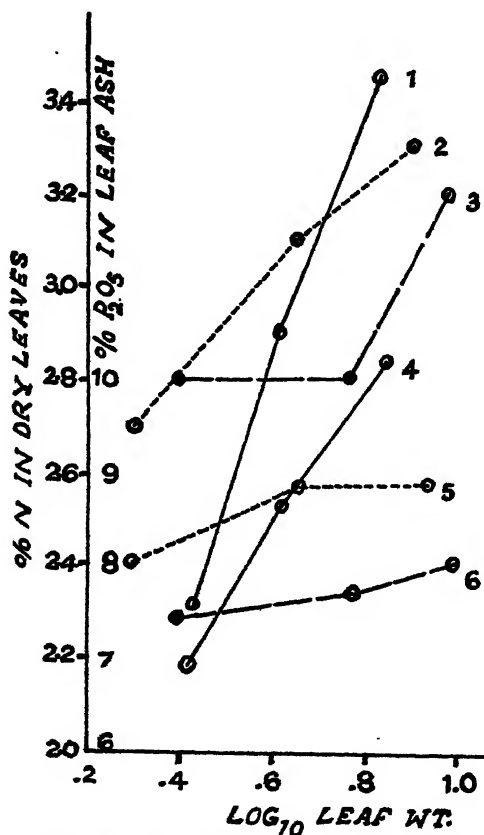
Fig. 1. Relation Between log₁₀ Leaf Weight of Seedlings and Percentage of Nitrogen in Dry Leaves and Percentage of P₂O₅ in Leaf Ash

Curves 1 to 3 show the nitrogen relationship and 4 to 6 that for phosphate for whorls 2, 3, and 4.

In figure 1 nitrogen in dry leaves and phosphate in leaf ash are both plotted against log₁₀ leaf weight for whorls 2, 3, and 4 (curves 1 to 3 and 4 to 6 respectively). It will be noticed that in the figures for both N and P₂O₅ the relationship is most exact for the youngest mature whorl. The decreased slope of the curve given by the older whorls indicates that nutrients are preferentially withdrawn from the leaves richest in them.

In a more detailed investigation six leaves of different sizes were taken in succession from the top to the bottom of the first mature whorl and were analyzed for N, P, and K. The results are shown in table 1. The correlation coefficients between $\log_{10}$ leaf weight and composition were: N and $\log_{10}$ leaf weight .889 ($P = .02$), P_2O_5 and $\log_{10}$ leaf weight .846 ($P = .05$). Potash showed a statistically insignificant correlation. A number of similar leaf groups from single whorls have been investigated. With one exception, they were all similar.

TABLE 1

Distribution of nutrients in the foliage of rubber seedlings

LEAF NUMBER (WHORL 2)	N IN DRY LEAVES	P_2O_5 IN LEAF ASH	K_2O IN LEAF ASH	GREEN LEAF WEIGHT	$\log_{10}$ LEAF WEIGHT
	per cent	*per cent*	*per cent*	*gm.*	
1	3.20	9.12	28.42	1.86	.27
2	3.36	9.82	29.28	3.48	.54
3	3.39	9.58	27.33	5.63	.75
4	3.59	10.28	28.70	8.86	.95
5	3.60	10.46	28.79	10.79	1.03
6	3.88	11.29	30.16	10.98	1.04

The following explanation is tentatively offered for the logarithmic relation between leaf weight and composition. It is based on the findings of Blackman (1) for unrestricted growth rate. He showed that:

$$\log \frac{W}{Wo} = rT$$

where Wo = initial weight
W = final weight
T = time growing
r = the fraction of the total dry weight added by growth in unit time.

It must be assumed that for any given whorl the factors in an equation of the above form, other than r and W, remain constant. If the value of r is directly proportional to the percentage of certain nutrients in the leaf or leaf ash, then clearly a simplified equation of the following form will fit the data when growth is limited by the supply of these nutrients:

$$\log W = k \text{ per cent nutrients} + c$$

where k and c are constants.

The largest initial leaves in each whorl are formed while reserve nutrients in the plant are plentiful. For the higher, later-formed leaves in the whorl, progressively smaller quantities of these nutrients are available, and hence the leaves become progressively smaller toward the apex of each whorl.

The logarithmic relationship at first sight tends to obscure the simple straight line relation between nutrient content and growth rate described below. But

the foregoing considerations show that it still holds, since we are here dealing
with the equivalent of an autocatalytic reaction in which the initial velocity
is still linearly related to leaf composition.

PRELIMINARY POT EXPERIMENTS

In preliminary pot experiments 4-gallon tins were filled with exhausted soil
from old plantations, and two plants were established in each tin. A factorial
layout was used to give 27 treatments with all possible combinations of nitro-
gen, phosphate, and potash at three levels, 0, 1, and 2. Fifteen such experi-
ments were laid out. Nitrogen was supplied as ammonium sulfate; potash,
as potassium sulfate; and phosphate, as Christmas Island phosphate.[3] The
fertilizer levels, in ounces per tin, were as follows:

Ammonium sulfate	Christmas Islan phosphate	Potassium sulfate
0	0	0
$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
1	$\frac{3}{4}$	1

Leaf sampling was begun after 6 months. The later experiments, which
were not sampled until the plants had become pot-bound, showed little cor-
relation between leaf composition and fertilizer treatment. It was subse-
quently shown in the field that the leaves of plants suffering from waterlogging
or drought were often low in nutrients in spite of heavy fertilizing and that
leaf composition was not then correlated with growth.

Tables 2, 3, and 4 give, respectively, typical results for nitrogen, phosphate,
and potash. The data in tables 2 and 3 are averages of three experiments
each, and those in table 4 are from a single experiment. In the statistical
analysis the symbols and the method are those used by Yates (19). From the
three tables the following interactions are apparent: Phosphate depresses nitro-
gen in the dry leaf (table 2); K depresses, and N increases, P in leaf ash (table
3); P depresses K in leaf ash (table 4).

All these interactions have been confirmed on rubber under field conditions
and several on other species, but it should be noted that they vary greatly in
intensity with soil type and other local conditions. The depression of P by
K in the leaf ash, for example, although often a very intense reaction, appears
to be totally absent or actually reversed on one abnormal soil type with a very
low silica/sesquioxide ratio for the clay fraction.

From table 2 there is some suggestion that K depresses N in the absence of
P, but the effect fails to attain statistical significance. Since KN is a fertilizer
combination that is never used for rubber, the indication has not been investi-
gated further.

[3] Christmas Island phosphate is a very soft rock phosphate containing 35 per cent P_2O_5.
Under Malayan conditions the phosphate is highly available.

FIELD EXPERIMENTS

Rubber younger than 2 years

The field experiments with rubber younger than 2 years were all carried out on exhausted soils from which the derelict stands of old rubber had been re-

TABLE 2

Percentages of N in dry leaves

Averages of three experiments

| | P 0 | | | P 1 | | | P 2 | | | AVER-AGE |
	K 0	K 1	K 2	K 0	K 1	K 2	K 0	K 1	K 2	
N 2	3.35	3.21	3.12	2.75	2.97	3.16	2.61	2.93	3.18	3.03
N 1	3.44	2.90	2.64	3.11	3.08	2.88	2.78	2.72	2.98	2.95
N 0	3.33	3.12	2.86	2.36	2.76	2.98	2.76	2.98	2.54	2.85
	3.37	3.08	2.87	2.74	2.94	3.01	2.72	2.88	2.90	
		3.11			2.90			2.83		

	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	t VALUE	P VALUE
Linear response................	3	.4861	.162	6.40	.01
Curvature.....................	3	.0387	.013	.51	....
Linear interaction.............	3	.4067	.135	5.34	.02
Linear × curvature............	6	.4216	.070	2.77	.05
Curvature × curvature........	3	.1400	.047	1.85	....
W, X, Y, Z (error).............	8	.2021	.0253		
	26	1.7502			

N............................	2	.1406	.0703	2.78	....
P............................	2	.2671	.1336	5.28	.05
K............................	2	.0061	.0031	.12	....
NP...........................	4	.2610	.0653	2.58	.05
NK...........................	4	.2579	.0645	2.55	.05
PK...........................	4	.6590	.1648	6.51	.005
W, X, Y, Z (error).............	8	.2021	.0253		
	26	1.7502			

| | LINEAR RESPONSE | | CURVATURE | | INTERACTIONS | |
	Mean square	P value	Mean square	P value	Mean square	P value
N................	.4213	.05	.0005	....	.1681	....
P................	1.0334	.02	.1013	....	.0012	....
K................	.0037	...	.0145	....	1.0506	.02

P depresses N.

moved shortly before the replanting experiments were begun. Maximum growth was always obtained without potash, but on some estates phosphate was still deficient after relatively enormous applications, and on others it was

difficult to supply adequate nitrogen.   The mechanical analyses and the silica-sesquioxide ratios of the soils are given in table 8.

TABLE 3

Percentages of P_2O_5 in leaf ash

Average of three experiments

	P 0			P 1			P 2			AVER-AGE
	K 0	K 1	K 2	K 0	K 1	K 2	K 0	K 1	K 2	
N 2	4.47	3.69	2.96	4.96	4.06	3.45	6.06	3.60	3.33	4.06
N 1	3.69	3.39	2.89	6.03	3.68	3.64	6.67	3.99	3.35	4.16
N 0	3.60	2.77	2.61	3.93	3.45	3.12	4.69	3.01	2.62	3.32
	3.92	3.28	2.82	4.97	3.73	3.40	5.81	3.53	3.10	
	3.34			4.03			4.15			

	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	*t* VALUE	P VALUE
Linear response.................	3	19.93	6.64	68.1	.001
Curvature.....................	3	3.21	1.07	11.0	.005
Linear interaction.............	3	2.25	.75	7.7	.01
Linear × curvature.............	6	1.81	.30	3.1	.05
Curvature × curvature.........	3	.21	.07	.7	....
W, X, Y, Z (error).............	8	.78	.0975		
	26	28.19			
N.............................	2	3.82	1.91	19.5	.01
P.............................	2	3.43	1.72	17.5	.01
K.............................	2	15.88	7.94	81.4	.001
NP............................	4	.80	.20	2.1	....
NK............................	4	.77	.19	1.9	....
PK............................	4	2.77	.69	7.1	.005
W, X, Y, Z (error).............	8	.78	.0975		
	26	28.25			

	LINEAR RESPONSE		CURVATURE		INTERACTIONS	
	Mean square	P value	Mean square	P value	Mean square	P value
N.................	7.66	.01	3.81	.02	.88	....
P.................	8.76	.01	1.53	.05	.07	....
K.................	43.36	.005	4.29	.02	5.81	.01

K depresses P; N increases P.

Areas in which phosphate deficiency was a limiting factor will be considered first.   On estate A, four treatments were laid out with replications in randomized blocks, and increase in height and leaf composition were followed throughout the season.   Growth was found to be linearly related to P_2O_5 in leaf ash; the correlation coefficient between these two variables for treatments

was .994 $(P = .001)$.   The nitrogen content of the leaves showed no correlation with any other variable measured.

TABLE 4

Percentages of K_2O in leaf ash

Results of a single experiment

	P0			P1			P2			AVER-AGE
	K0	K1	K2	K0	K1	K2	K0	K1	K2	
N2	29.2	37.5	36.9	22.5	40.0	36.9	16.6	34.9	31.1	31.7
N1	30.4	35.3	36.3	20.8	37.1	37.0	13.7	30.1	37.5	30.9
N0	29.0	43.3	45.4	24.4	33.1	34.1	18.1	27.7	37.7	32.5
	29.5	38.7	39.5	22.6	36.7	36.0	16.1	30.9	35.4	
		35.9			31.8			27.5		

	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	t VALUE	P VALUE
Linear response................	3	1235.99	411.99	48.76	.001
Curvature....................	3	195.65	65.22	7.72	.01
Linear interaction.............	3	86.29	28.76	3.40	.05
Linear × curvature...........	6	64.81	10.80	1.28	....
Curvature × curvature........	3	15.10	5.03	.60	....
W, X, Y, Z (error)............	8	67.61			
	26	1678.69			
N...........................	2	12.48	6.24	.74	....
P...........................	2	320.70	160.35	18.98	.01
K...........................	2	1100.37	550.19	65.11	.001
NP..........................	4	46.42	11.61	1.34	....
NK..........................	4	36.94	9.24	1.09	....
PK..........................	4	75.23	18.81	2.23	....
W, X, Y, Z (error)............	8	67.61	8.45		
	26	1678.69			

	LINEAR RESPONSE		CURVATURE		INTERACTIONS	
	Mean square	P value	Mean square	P value	Mean square	P value
N.................	8.64	....	26.89	....	20.70	....
P.................	960.13	.01	.07	....	43.56	....
K.................	2739.21	.01	560.01	.01	194.60	.05

P depresses K.

On estate B phosphate is also the limiting factor but is much more easily supplied than on estate A.   On estate B the correlation coefficient of nitrogen in dry matter and P_2O_5 in leaf ash for treatments was .999 $(P = .001)$.   Clearly on this estate growth and the two nutritional factors are all correlated with one another.

On estate C nitrogen is the limiting factor, and phosphate in ash normally shows no correlation with growth rate. The correlation coefficients between nitrogen in dry leaf and growth rate for treatments were .913 ($P = .02$) and .994 ($P = .001$) for experiments in 1938 and 1940 respectively.

The reciprocal effect, reduction of leaf potash by phosphatic fertilizer treatment, is also observable. In a recent factorial experiment containing 64 plots, the ½- and 1-pound Christmas Island phosphate treatments applied in the planting hole 2 months before planting and at the time of planting were compared in addition to four subsidiary treatments which need not be considered here. It was found that 1 pound did not produce a significantly greater potash depression than did ½ pound if the phosphates were applied at the time of planting; but if they were applied 2 months earlier, K_2O in leaf ash was 1.5 per cent ($P = .02$) lower for the plants receiving the heavier dressing, when their leaves were analyzed 4 months later. Comparison of 1 pound applied 2 months before planting with 1 pound applied at the time of planting showed that the earlier dressing produced a depression over the latter of 1.1 per cent K_2O ($P = .02$) in leaf ash. Since there was no statistically significant difference in the leaf phosphate for the four treatments, these data certainly support some hypothesis which places the seat of depression outside the plant.

Mature rubber

The work on mature rubber indicates that the nutritional requirements of the rubber plant remain essentially constant throughout life. In young rubber the only vital function studied was growth, whereas in the mature tree latex yield could also be measured. That the yield of mature rubber is but slowly affected by changes in the nutrition of the tree increases the difficulty of studying the relationship between these two variables in a short time. Results have therefore been less consistent in old than in young rubber. Another difference between the fertilizing of seedling and mature rubber is the relative quantity of fertilizer used. In most of the experiments quoted on rubber seedlings the fertilizer applications were only slightly below the optimum, but economic considerations usually keep the dressings applied to large trees at a much lower level.

NITROGEN AND YIELD

Leaf nitrogen is often correlated with yield, though as has already been mentioned, the nitrogen content of the leaves varies with many factors, including the time of the year. Fertilizer treatments have an important bearing on the annual cycles through which leaf composition passes. It is often found that in one part of the season a high correlation is shown between leaf nitrogen and yield, whereas at another time the correlation may fail to be statistically significant, though an inverse correlation has never been observed. With this qualification in mind, the following two cases may be cited of significant correlations between yield and leaf nitrogen. On estate H in an experiment

with the following four treatments: 1, control; 2, ammonium sulfate; 3, Christmas Island phosphate; 4, ammonium sulfate + Christmas Island phosphate, the correlation coefficient was .860 ($P = .01$) between leaf nitrogen and yield for single plots.

On estate G an experiment with the following three treatments: 1, control; 2, ammonium sulfate; 3, sodium nitrate, yielded a correlation coefficient of .823 ($P = .05$) for single plots.

Phosphatic fertilization depresses the leaf nitrogen of mature rubber as it did in the preliminary pot experiments already described. Since yield is correlated with leaf nitrogen, it therefore follows that the immediate effect of phosphatic fertilization combined with nitrogenous, is to depress the yield below the level obtained with nitrogen alone. This explains the result obtained many years ago by Grantham (7)

The action is paralleled by the effect of potash in depressing leaf phosphate, and with it growth, under conditions of phosphate deficiency. It is unlikely that either of these results is universal. Extreme cases probably exist where phosphate is so low that nitrogen alone will be without effect. But such cases have not so far been encountered in the field, undoubtedly because of the ability of nitrogen to liberate soil phosphate.

GROWTH RATE IN MATURE RUBBER

Although the data are less complete for mature than for young rubber, there are indications that the same general principles apply as have been shown to hold for young rubber.

On estate D an experiment was laid down which included the following three treatments: 1, ammonium sulfate; 2, ammonium sulfate + Christmas Island phosphate; 3, ammonium sulfate + Christmas Island phosphate + potassium sulfate. The growth of the trees was found to be correlated with the phosphate content of their leaves. (Correlation coefficient for single plots = .887, $P = .001$.) When the graph was extrapolated to zero growth rate, it gave a value for the leaf of approximately 3 per cent P_2O_5. Graphs from other experiments have given values between 3 and 4 per cent P_2O_5 in leaf ash. An analysis of the leaves from derelict trees which had stopped growing and were dying of phosphate starvation gave the value of 3.6 per cent P_2O_5, in good agreement with the prediction from the curves.

The data are less complete regarding the influence of leaf nitrogen on the growth rate of mature rubber. Another complication here is the fact that the application of nitrogenous fertilizers increases leaf phosphate as it does in young rubber. The magnitude of this increase is seen from the results of another experiment on the same estate, in which the percentages of P_2O_5 in the ash were as follows: control, 4.89; ammonium sulfate treatment, 5.52; ammonium sulfate + Christmas Island phosphate treatment, 6.36; difference for significance ($P = .05$) = .11.

On estate G the following results were obtained (percentages of P_2O_5 in ash):

control, 4.96; ammonium sulfate treatment, 6.01; sodium nitrate treatment, 5.66; difference for significance $(P = .05) = .54$.

The effect is largely responsible for the surprisingly good results obtained from applications of nitrogen alone, although the rubber is usually deficient in phosphate as well as nitrogen.

DEPRESSING EFFECT OF PHOSPHATIC FERTILIZATION ON LEAF POTASH

Phosphatic fertilization on some soils depresses leaf potash in mature rubber as seriously as it did in the preliminary pot experiments. The following figures (percentages of K_2O in ash) from a randomized block experiment with four replications represent an extreme example: control, 27.92; ammonium sulfate treatment, 27.35; ammonium sulfate + Christmas Island phosphate, 19.33; ammonium sulfate + potassium sulfate, 26.56; ammonium sulfate + Christmas Island phosphate + potassium sulfate, 21.70; difference for significance $(P = .05) = 1.89$.

TABLE 5

Leaf composition as affected by difference in time of phosphate application

TREATMENT	N IN DRY LEAVES	P₂O₅ IN LEAF ASH	K₂O IN LEAF ASH
	per cent	*per cent*	*per cent*
A. N + P....................................	3.06	6.66	30.11
B. N + P (1 month later).....................	3.23	6.95	31.56
C. N + P (2 months later)....................	3.18	6.59	30.76
D. N + P (3 months later)....................	3.29	6.96	31.23
E. N only...................................	3.28	5.68	34.90
Difference for significance $(P = .05)$	.08	.33	1.00

On estate F a 5 by 5 latin square was laid down to determine the effect on leaf composition of the time of application of phosphate in relation to that of ammonium sulfate. The treatments were as follows:

A = ammonium sulfate + Christmas Island phosphate (simultaneous application)
B = ammonium sulfate + Christmas Island phosphate (applied 1 month later)
C = ammonium sulfate + Christmas Island phosphate (applied 2 months later)
D = ammonium sulfate + Christmas Island phosphate (applied 3 months later)
E = ammonium sulfate only.

After two annual applications of fertilizer the experiment was leaf sampled. The results are given in table 5. It will be observed that phosphate exercises its usual depressant action on potash absorption, and that nitrogen is depressed if the two fertilizers are applied together. If phosphate is applied several months after the ammonium sulfate, however, potash is reduced less by the phosphate, and nitrogen not at all. Phosphate absorption would appear to be relatively unaffected.

Though potash generally depresses phosphate in mature as in young rubber, one possible exception, which however does not attain statistical significance, has been encountered. In an experiment on estate H with the following treatments:

1. Ammonium sulfate
2. Ammonium sulfate + Christmas Island phosphate
3. Ammonium sulfate + potassium sulfate
4. Ammonium sulfate + Christmas Island phosphate + potassium sulfate

growth rate was negatively correlated with leaf ash potash (correlation coefficient $-.858$, $P = .01$). This is in accordance with known facts concerning the rubber which was dying of starvation at the beginning of the experiment and in which the primary deficiencies were certainly nitrogen and phosphate. In the light of the foregoing facts it was therefore to be expected that the addition of potash would render the phosphatic fertilizer less efficient.

SOIL FACTORS AFFECTING THE ABSORPTION OF NITROGEN

The following experiments, selected from a number carried out during preliminary work with the same commercial fertilizers that were used in the field, were designed to answer the question: Are the observed interactions of the different fertilizer elements due to reactions taking place in the soil or in the plant? Because they show clearly the importance of phosphates to the mobility of ammonical nitrogen in Malayan soils, they are included here. Further work is being done, however, and will be described more fully later.

It has already been noted that if phosphates are given in addition to nitrogen, less nitrogen is absorbed than from the nitrogenous fertilizers alone. This strongly suggests that the effect is due to a lowering of nitrogenous substances in the soil solution by the addition of phosphatic fertilizers. But it was considered advisable to obtain additional evidence from a totally different angle.

Several series of leaching experiments were therefore started in inverted bottles from which the bottoms had been removed. The bottles were packed with exhausted soils similar to those on which field experiments were cited and were allowed to settle for 3 months with occasional watering until the leachings were virtually nitrogen-free before the experiments were begun. Duplicate bottles were set up for all soils. The fertilizers were then added, watered, and left to react with the soil for 5 days before leaching was started. All fertilizer applications were calculated on a basis of hundredweight per acre, and in series 1 the soil columns were 4 inches deep. Three leachings, each with 100 cc. water, were carried out at intervals of 4 days. The fertilizer applications and the total quantities of nitrate and ammonia nitrogen removed from the soil are given in table 6. The quantity of nitrate removed is little affected by the other elements present in the fertilizer, but from all three soils

the ammonia nitrogen is less easily lost from the compound concentrated fertilizer.

TABLE 6

Fertilizer applications to soil columns and nitrogen lost in drainage water

SOIL TYPE	TREATMENTS, PER ACRE
1. Friable chocolate loam	(i) 2.5 hundredweights P_2O_5 (as Christmas Island phosphate) $+$ 0.5 hundredweight N (as ammonium sulfate)
	(ii) 1.5 hundredweights P_2O_5 $+$ 0.5 hundredweight N (as concentrated fertilizer X *)
2. Sandy yellow loam	Same as in 1.
3. White stiff clay	Same as in 1.

	NITROGEN IN DRAINAGE WATER	
	NO$_3$-N	NH$_3$-N
	gm.	gm.
Friable chocolate loam:		
Treatment i.....................................	.0028	.0048
Treatment ii....................................	.0029	.0028
Sandy yellow loam:		
Treatment i.....................................	.0031	.0313
Treatment ii....................................	.0031	.0167
White stiff clay:		
Treatment i.....................................	.0022	.0267
Treatment ii....................................	.0031	.0018

* This concentrated commercial fertilizer contained approximately 41 per cent P_2O_5 and 14 per cent N and was compounded from triammonium phosphate with 10 per cent ammonium sulfate.

TABLE 7

Effect of phosphate on penetration of NH$_3$-N into sandy yellow loam

TREATMENT, PER ACRE	NH$_3$-N IN DRAINAGE WATER TO SOIL LAYER DEPTH OF		
	3 inches	6 inches	9 inches
	gm.	gm.	gm.
0.5 hundredweight N (as ammonium sulfate).................	.0540	.0127	.0003
0.5 hundredweight N (as ammonium sulfate) + 2.5 hundredweights P_2O_5 (as Christmas Island phosphate)............	.0403	.0039	.0007
0.5 hundredweight N + 1.5 hundredweights P_2O_5 (as concentrated fertilizer X*)....................................	.0289	.0006	.0001

* See footnote table 6.

In series 2 nitrogen was applied at the same rate per acre, but ammonium sulfate alone was included, and soil columns 3, 6, and 9 inches deep were used. The effect of phosphate, whether applied as rock or as soluble phosphate, is

very pronounced in reducing the penetration of ammonia into the soil, as shown in table 7.

No theories are put forward to account for these observations, as they are described here solely for their bearing on the leaf analysis data.

TABLE 8

Analyses* of soil types on which field experiments were run

ESTATE	SOIL TYPE	$\frac{SiO_2}{Al_2O_3 + Fe_2O_3}$	STONES	SOIL AFTER REMOVAL OF STONES					
				Coarse sand	Fine sand	Fine silt	Clay	Loss on ignition	Total
			per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
A	Sandy yellow loam	1.08	.....	69.45	7.05	7.34	9.18	3.71	96.73
B	Yellow clay	0.84	.....	32.98	32.65	7.67	18.68	6.04	98.02
C	Ironstone gravel	0.88	75.10	13.30	18.10	22.50	35.60	8.60	98.10
D	White stiff clay	1.25	.....	6.62	43.60	32.90	18.80	3.80	105.72
E	Friable chocolate loam	0.59	.....	3.93	1.73	9.35	70.07	14.20	99.28

* The grading of the fractions in the mechanical analyses were according to the limits laid down in the English method. The settling times were reduced to accord with the viscosity of water at 25°C.

DISCUSSION

From the data presented it is clear that for the tree species studied the relation between ultimate leaf composition and nutritional status as exemplified by growth rate is often linear.

Nutrient balance in the fertilizers applied is of considerable importance because of the interactions which have been shown to exist among nitrogen, phosphate, and potash in determining the absorption of these nutrients from the soil. This is well shown by the depression in leaf nitrogen when phosphate is added to the nitrogenous fertilizer and by the depression of leaf phosphate when potash is applied with the phosphate. There is no evidence, however, that balance between the nutrients is important within the plant as distinct from the reactions proceeding in the soil outside. The relations between leaf composition and growth rate appear to be governed by the law of minimum factors. As mentioned earlier, these results appear to differ radically from those of Thomas and Mack (16, 17), but in the writer's opinion this difference is due to a difference in the range of composition studied by the two workers. Long before either work was started, the writer accepted the general hypothesis that balance within the plant is of the utmost importance and was somewhat surprised to find that the data presented in this paper could be more satisfactorily explained on the basis of Liebig's law of minimum factors than on any theories of balance. Although these relations have been discussed in connection with field experiments, they clearly have much wider applications. The

following example will serve to illustrate one of the practical applications to which the technique can be applied:

Patches of varying growth can be selected in the field, and girth or height measured and leaf composition determined. Growth is then found to be correlated with the leaf content of the deficient element. Where inferior growth has been known to be due to factors other than nutrition, none of the nutrients determined has shown a close correlation with growth.

SUMMARY

A technique is described for studying the relations existing between the nutritional status of a plant and the nitrogen, phosphorus, and potassium content of its leaves. In describing and illustrating the general application of this technique, details that would be of no interest outside the rubber industry are omitted.

Some of the factors other than nutrition which influence leaf composition are described with their bearing on leaf sampling. The importance of using rapid chemical methods which permit analysis of a large number of samples is emphasized, and it is shown from statistical analysis that these methods need only attain a moderate standard of accuracy.

A series of factorial pot experiments is described in which the interactions of the three nutrients N, P, and K are studied in relation to leaf composition.

In a series of field experiments, the leaf composition and growth rate of seedling rubber are shown to be correlated. In mature rubber, similar relations exist. Latex yield is shown to be correlated especially with leaf nitrogen, and under certain conditions both are depressed by phosphatic fertilization.

The effect of phosphates on the penetration of ammonia nitrogen into the soil is shown to be very marked. This is held to support the theory that the depression of nitrogen absorption by phosphatic fertilization is primarily a soil phenomenon.

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BOOKS

Agrochemistry. Third Edition. By D. H. PRIANISHNIKOV. Gosizdat, Moscow, 1940. Pp. 644, figs. 77. Price, 20.75 rubles.

This is the third, greatly enlarged edition of Prianishnikov's famous book on agricultural chemistry. The book is divided into three parts. Part I, dealing with plant nutrition and soil properties, contains the following chapters: Development of our ideas on plant nutrition; the role of individual elements; the entrance of substances into plants from the surrounding medium; on the nutrition of plants with ammonium and nitrate nitrogen; nutrient mixtures for the growth of plants in artificial media; variation and the capacity of plants to assimilate nutrients from difficultly soluble compounds; the adsorbing capacity of soils; the influence of reaction and other soil properties on the composition of the soil-adsorbing complex; organic matter of the soil; removal of nutrient substances from the soil by a crop and its replacement by means of fertilizers; Part II: nitrogen fertilizers; phosphatic fertilizers; potash fertilizers; complex fertilizers; lime; the utilization of gypsum, sulfur, and sodium chloride as fertilizers; fertilizers containing boron, manganese, and copper; complete fertilizers of organic origin; on the application of fertilizers in special rotations; Part III: field experiments with fertilizers; the vegetation method and its fundamental role in agrochemical investigation. The book also has a section by Prof. D. V. Druzhinin on care and mixing of fertilizers.

Intended primarily as a text for advanced students in agricultural institutions, the book has only a very limited bibliography and no indexes. It is well printed.

S. A. W.

Chemistry. By WILLIAM McPHERSON, WILLIAM E. HENDERSON, W. CONRAD FERNELIUS, AND EDWARD MACK. Ginn and Company, New York, 1940. Pp. 762, illus. 379. Price, $3.75.

A college text book designed to give freshmen a glimpse into the intricacies of chemical phenomena without making the subject unduly difficult. One of the most interesting departures from the usual is the insertion of several pages of arithmetic for the many students who have never learned how to use percentages, fractions, and proportions. The text includes more than the usual amount of organic chemistry. The illustrations are well chosen and add interest to the discussion.

The Classification of Land. Proceedings of the First National Conference on Land Classification. Bulletin 421, Missouri Agricultural Experiment Station, Columbia, 1940. Pp. 334.

Conceived by Dr. Conrad H. Hammar, University of Missouri, this conference had for its purpose the discussion of land classification problems in relation to such needs as appraisal for credit purposes, for real estate assessment, for rural and urban-rural zoning, for forest, grazing, reclamation, conservation, farm management, and general land use, and for recreational purposes. Some 48 specialists in these several fields took part in the conference. The published report gives a modernized version of the problems involved and the techniques that are employed in their solution.

Farm Soils—Their Fertilization and Management. By EDMUND L. WORTHEN. John Wiley and Sons Co., New York, 1941. Pp. 515, illus. 226. Price, $2.75.

Written by a man who has devoted his life to aiding farmers in the solution of their soil problems, this book contains the answers to most of the questions which the practical man would ask about the management of his land. Packed into its pages is a wealth of experience which most experiment station agronomists will read with profit.

Hunger Signs in Crops. A joint publication of The American Society of Agronomy and the National Fertilizer Association. Judd and Detweiler, Washington, D. C., 1941. Pp. 327, figs. 95, color plates 79. Price, $2.50.

A remarkable new book which marks an epoch in the advancement of our knowledge of the nutritional needs of crop plants as revealed by the external symptoms of nutrient deficiencies. Each of the nine chapters of this book was written by a man, or a group of men, particularly well informed on the plant or plants in question. Special consideration is given to deficiency symptoms of tobacco, corn, small grains, potatoes, cotton, truck crops, deciduous fruits, legumes, and citrus. The color-plate exhibit is the finest collection of natural-color reproductions which has ever been assembled. Every plant scientist and every scientific farmer will want a copy of this book for ready reference.

Maintenance of Shade and Ornamental Trees. By P. P. PIRONE. Oxford University Press, New York, 1941. Pp. 422, illus. 73. Price, $4.50.

An exceptionally well illustrated book dealing with the principles involved in the growing and care of fine trees. While specific instructions are given in relation to the planting, fertilizing, pruning, and repairing of trees, the author's greatest concern is in relation to abnormalities of trees as effected by insects and disease, and the means by which these destructive agents can be kept under control. All lovers of trees will want a copy of this attractive and useful book.

Plant Ecology. By W. B. McDOUGALL. Lea and Febiger, Philadelphia, 1941. Pp. 285, illus. 118. Price, $3.

A thoroughly revised edition of this interesting and attractive book which deals with plants in relation to their environment. The subject is so developed

as to make it particularly interesting to those who are concerned with crops and soils.

Soil Mechanics. By DIMITRI P. KRYNINE. McGraw-Hill Book Company, Inc., New York, 1941. Pp. 451, illus. 316. Price, $5.

The fundamentals of soil mechanics, including a discussion of the physical properties of soils in relation to stresses and strains involved in foundations, embankments, and retaining walls. The book is written primarily for civil engineers but contains factual material of considerable interest to soil physicists and soil conservationists.

THE EDITORS

CHICAGO UNIVERSITY TO MARK SEMICENTENNIAL

The Fiftieth Anniversary Celebration of The University of Chicago, the theme of which will be "The Frontiers of Knowledge in the Geologic Sciences," will devote one session, September 25, 1941, to "Frontier Researches on the Structure, Properties, and Occurrences of Clay Materials and Their Practical Application," according to Dr. Edson S. Bastin, Chairman, Department of Geology and Paleontology, of that university.

For this session, to be held in Room 2, Rosenwald Hall, from 9 a.m. to 12:15 p.m., the following subjects have been announced: "Modern Concepts of Clay Materials," by Ralph E. Grim, Illinois Geological Survey, Urbana; "The Relation of the Lattice Structure of Clay Minerals to Some Properties of Clays," by Sterling B. Hendricks, Bureau of Plant Industry, U. S. Department of Agriculture; "Applications of Modern Clay Researches in Agriculture," by Walter P. Kelley, College of Agriculture, University of California; "Applications of Modern Clay Researches in Ceramics," by F. H. Norton, Department of Metallurgy, Massachusetts Institute of Technology; "Applications of Modern Clay Researches in Construction Engineering," by Hans. F. Winterkorn, College of Engineering, University of Missouri.

A REVISED NOMENCLATURE OF FOREST HUMUS LAYERS FOR THE NORTHEASTERN UNITED STATES

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Early in June 1939, a conference of soil scientists and foresters was called at Petersham, Massachusetts[2], for the exchange of views on the soil as a factor in forest practice. The humus layer problem was among those discussed, and it was pointed out that changes in nomenclature made it impossible to turn to any single publication as a reference on forest humus layers. It was agreed that an up-to-date descriptive summary of the frequently occurring humus layer types of the Northeast would be helpful, and that such should be published so as to be available for distribution to soil surveyors. In order to secure action on this problem, a committee was appointed to draw up such an article. The material which follows is the result of this committee's action. An attempt has been made to describe the various types in sufficient detail to enable the soil surveyor to recognize these types in the field without the assistance of one experienced in their identification. No new material is given, but rather that which has been published is coordinated and unified.

The first comprehensive study of forest humus layer types in the Northeastern United States was published by Romell and Heiberg in 1931 (9). This study was built upon P. E. Müller's classical works "Studier over Skovjord" published in 1878 and 1884 (7, 8). Morphological characters which could easily be recognized in the field were used for identification. This work (Romell and Heiberg) has served as a basis for all other nomenclatures proposed for the Northeastern United States. This statement applies, as well, to the suggestions made in this paper.

Romell and Heiberg used the word "duff" to indicate unincorporated humus layer types. In a more recent publication by Bornebusch and Heiberg (1) and as restated later by Heiberg (2), the word "duff" was changed to Müller's original "mor." The reasons for this change were that the word "duff" was

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[1] Although this article was originally organized and written by those indicated as authors, the final product is a result of the valuable suggestions of the other members of the committee appointed to revise the nomenclature of the forest humus layers. These persons are as follows: T. S. Coile, P. R. Gast, H. A. Lunt, and H. J. Lutz.

The authors wish to thank L. Gysel for the use of the photographs reproduced in plate 1, figure 3, and in plate 2, figures 2 and 3.

[2] Summary report, mimeographed, obtainable in limited quantity from the Northeastern Forest Experiment Station.

used in a different sense by American foresters, and it was not well adapted for international use. In this classification system, only those types which appear to be common to both North America and Northern Europe were given as examples. In addition, the names of certain of the types described by Romell and Heiberg (9) were changed so as to be more descriptive as well as to facilitate their translation into other languages.

If one wished to use the system of Bornebusch and Heiberg he was limited by the fact that certain rather common types were not listed. If one decided to use Romell and Heiberg as a standard, he would have to make certain changes in order to use the most recently approved terminology. It is hoped that this article will provide one authority which combines the good features of all nomenclatures that have been proposed for the Northeastern United States. In this revision, one will note many repetitions of what has already been published. This is mainly for the convenience of the reader, thus avoiding the necessity of any continual reference to other sources. It must be remembered that this classification applies only to forest humus layers of well-drained, upland soil (1). The humus layers of forest swamps and bogs have not yet been classified.

The term "humus layer" is defined as the surface soil which is characterized largely by its organic matter content. It includes the A_0 horizon below the litter[3], and in the case of a mull, part or all of the A_1 horizon. Any horizon deeper in the profile which contains a mixture of organic matter, as often found in the B_1 horizon of a podzol profile, is not included in the humus layer.

In order to describe or identify humus layers properly it is necessary to recognize the F and H layers as described by Hesselman (5). The F layer consists of more or less decomposed forest litter still recognizable as to origin (pl. 1, fig. 1). The H layer consists principally of organic matter mostly unrecognizable as to origin (pl. 1, fig. 2). The F and H layers make up the A_0 horizon. The H layer may be absent, for when the finely divided organic matter is mixed with mineral soil it becomes a part of the A_1 horizon and is no longer considered as an H layer.[4] Humus layers, in soil classification terminology, consist of the A_0 and A_1 horizons to the extent that both are present. The object in classifying humus layers is to make possible a more definite description of the characteristics of these horizons. For example, F and H layers vary in thickness, structure, and consistence. An F layer may be rather loose; it may be matted or compacted with a laminated structure; it may be fibrous, being held together by many fungal hyphae. An H layer may have a coarse or fine granular structure; it may be permeated by a tightly interwoven mass of roots; it may be thoroughly bound together by many fungal hyphae; it may be of an amorphous nature with a slippery, greasy consistence when wet. The A_1

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[3] Litter: freshly fallen leaves and other forest debris which have not yet shown visual evidence of decomposition.

[4] The soil horizon terminology employed in this paper is the same as that used by Kellogg (6).

horizon may vary in organic matter content and in structure and consistence. Under forest conditions the organic matter content may vary from 2 to 60 per cent. The more common structural conditions are crumb, granular, and single grain. Common consistence conditions in forest soils are loose or open, friable, crumbly or firm. Since the F and H layers (as components of the A_0 horizon) and the A_1 horizon may vary in a manner similar to the foregoing descriptions, it seems advisable to describe these horizons in more detail than is common in soil survey reports. It is hoped that the figures and descriptions presented in this paper will provide an example of how the commonly occurring humus layer types of the Northeastern United States have been classified and named. The name which is attached to a given humus layer condition is not so important as the description. The main objective is to direct attention to the variations in the morphological features of the A_0 and A_1 horizons of forest soils.

A brief descriptive outline of the nomenclature of forest humus layers which the committee proposes is given below:

Forest humus layers may be divided into two main groups: (I) mull, and (II) mor.

(I) *Mull*—A humus layer consisting of mixed organic and mineral matter. Transition to lower horizon not sharp.

Types recognized in this group:

a. Coarse mull: Coarse crumb or granular structure. Many granules about $\frac{1}{8}$ inch (2.0–3.0 mm.) or larger. Organic matter thoroughly mixed with mineral soil (usually 5–20 per cent organic matter; exceptional cases even higher). (Pl. 1, figs. 3, 4, 5.)

b. Medium mull: Medium crumb or granular structure. The larger granules about $\frac{1}{16}$ inch (about 2.0 mm.) or slightly smaller. (Pl. 1, fig. 5.)

c. Fine mull: Granular structure, frequently having the appearance of fine black sawdust. Rich in organic matter (usually over 50 per cent, but sometimes as low as 30 per cent). (Pl. 1, fig. 5; pl. 2, fig. 1.)

d. Firm mull: Dense, compact, and generally structureless, with a low content of organic matter (usually less than 5 per cent). (Pl. 2, fig. 2.)

e. Twin mull: A complex type consisting of one upper horizon of fine mull or matted mor (see below) underlain by an A_1 horizon having the characteristics of either medium or coarse mull. (Pl. 2, fig. 3.)

(II) *Mor*—A humus layer of unincorporated organic material, usually matted or compacted or both, distinctly delimited from the mineral soil unless the latter has been blackened by the washing in of organic matter. Types recognized in this group:

a. Matted mor: F layer thin, in some instances practically absent. Organic matter of the H layer finely granular as in granular mor or fine mull; when dry, virtually all of it can be shaken out from the dense root mat that holds it together. (Pl. 2, figs. 4, 5.)

b. Laminated mor: Thick laminated F layer of matted leaves. H layer much like matted mor.

c. Granular mor: H layer pronounced and of fine granular structure, lower part somewhat compacted. In dry condition, very easily broken into fine powder when crushed by hand. Distinguished from matted mor by the absence of a well-developed root mat. (Pl. 3, fig. 1.)

d. Greasy mor: F layer usually weakly developed, commonly more or less fibrous. H layer thick, compacted, with a distinct greasy feeling when wet. Hard and brittle when dry. (Pl. 3, fig. 2.)

e. Fibrous mor: F layer well developed; both F and H layers fibrous, more or less tough and felty, but not compact. Many plant remains may be visible in the H layer.

In order to clarify the relationships between the foregoing system of nomenclature and previously published ones, the equivalent types in each are shown in table 1.

In order to clarify further the distinctions between the various types, a more detailed description of each of the 10 types is given in the following paragraphs. The photographs of the various humus layer types are labelled on the right in accordance with forest soil terminology and on the left in accordance with the accepted terminology of the soil surveyor.

Coarse mull is readily recognized by its coarse crumb or granular structure. The organic matter is usually incorporated to depths ranging from 2 to 18 inches. Large earthworms such as *Lumbricus terrestris* L. are generally abun-

TABLE 1

The equivalent type names for each of the three nomenclatures for forest humus layers of the Northeastern United States

ROMELL AND HEIBERG]	BORNEBUSCH AND HEIBERG	HEIBERG AND CHANDLER
Crumb mull	Coarse mull	Coarse mull
Grain mull	. . . .	Medium mull
Detritus mull	Fine mull	Fine mull
. . . .	Firm mull	Firm mull
Twin mull	. . . .	Twin mull
Root duff	. . . .	Matted mor
Leaf duff	. . . .	Laminated mor
. . . .	Granular mor	Granular mor
Greasy duff	Greasy mor	Greasy mor
Fibrous duff	Fibrous mor	Fibrous mor

dant, and the results of their activity can be seen by observing the piles of leaves drawn up around their burrows.

In the richer coarse mull types, the leaves that fall one autumn are almost entirely disintegrated and incorporated into the mineral soil by the next leaf-fall period. The amount of natural reproduction is generally abundant. The more exacting hardwoods are common on this type. The pH of the soil is usually above 5.0. Variations from the foregoing description may occur occasionally. A photograph of the surface of a typical coarse mull is shown in plate 1, figure 4. A coarse mull profile occurring on Crosby silt loam soil in Ohio is shown in figure 3. The size of the larger granules can be readily seen in figure 5.

Medium mull is distinguished from coarse mull by its finer crumb or granular structure. The incorporation of the litter into the soil is not rapid as in coarse mull. The larger earthworms (*Lumbricus terrestris* L.) are either absent or few in number. This type is found under many old field hardwood stands. In

time it might develop into a coarse mull. Note the relative size of the larger granules in plate 1, figure 5.

Fine mull is best characterized by its high organic matter content. The incorporation of organic matter is to a shallow depth, but it is intense. Earthworms are usually absent, and smaller fauna seem to be responsible for the incorporation of the humus. Millipeds are rather common. In most cases a somewhat matted F layer 0.5 to 1 inch thick is present. Usually the H layer is very thin or absent, although in some cases a well-developed H layer occurs, having a fine granular structure and a diffuse lower boundary. The size of the particles in the A_1 horizon can be noted in plate 1, figure 5. A typical profile from the southeastern Adirondacks is shown in plate 2, figure 1.

Firm mull is generally poor in both amount and activity of soil fauna. Litter and F layer are thin or absent. The zone of incorporated humus is compact, massive, and biologically inactive. The organic matter content is low, and the depth to which it is incorporated is shallow. This type is common on ridge tops and sites exposed to sun and wind and is of low productivity. A typical firm mull in a grazed woodlot is shown in plate 2, figure 2.

Twin mull is poorly represented with respect to total area over which it occurs. It does occur with sufficient frequency, however, to warrant its description. The type is somewhat variable but usually consists of a thin F layer of matted leaves above an H layer that usually is finely granular and may or may not be permeated by an intense network of roots. Below the H layer is a thin layer of either coarse or medium mull. This type has often been observed in small areas within larger areas of matted or granular mor. These areas are usually somewhat better supplied with moisture than those which surround them. A twin mull developed under hardwood vegetation on Volusia silt loam is shown in plate 2 figure 3.

Matted mor is featured by a thin F layer (usually not over 0.5 inch) and by an H layer thoroughly permeated with fine roots. The roots are so interwoven that when a piece of mor of this type is cut out with a sharp instrument and shaken, the mat of roots still remains intact, even though the granules of H layer material fall out (note plate 2, figure 5). This formation of a stable root mat should distinguish this type from any others. Other mor types will be permeated with a large number of roots, but they will not hold together to such a marked degree. This type is common in the acid soils derived from shale and sandstone deposits in southern New York and northern Pennsylvania. A typical matted mor from Ohio is shown in plate 2, figure 4.

Laminated mor needs little description, as it is the same as matted mor except that it has a thick F layer. It does not occur to any great extent in the Northeast, but the thick, laminated layer of leaves is so characteristic that inclusion of the type seems advisable.

Granular mor was originally described by Heimbürger (4) as "granule mor." When it was first observed, it was not distinguished from greasy mor. Under careful observation, it was noted that certain types had a fine granular structure

in the greater part of the H layer, being finely divided and structureless only in the lower part. Individual granules vary in size, but the majority of them are about 1 mm. in diameter. A granular mor from the Adirondack section of New York is shown in plate 3, figure 1.

Greasy mor is a distinct type occurring rather consistently beneath pure hemlock and spruce stands in the acid soils of the Northeast. It may also occur beneath pine and pine-hemlock mixtures. The H layer is thick, in many places more than 6 inches. It is very slippery when rubbed between the fingers. In the Northeast, this type has always proved to be extremely acid in reaction, usually between pH 3.0 and 4.0. A typical profile beneath a pine-hemlock stand in the southeastern Adirondacks is shown in plate 3, figure 2.

Fibrous mor owes its nature both to the presence of a large number of fungal hyphae which permeate the humus layer, and to the presence of fibrous plant remains which have not undergone sufficient decomposition to lose all their original structure. The type is somewhat variable, but in all cases apparently fungal activity predominates and soil fauna are limited both in number and activity. The fibrous nature, although discernible in the F layer, is especially characteristic of the H layer. Other types may exhibit a fibrous condition in the F layer and yet not be classed as fibrous mor (see plate 3, figure 3).

In attempting to identify or describe humus layers, one should expect to find considerable variability within a given type, and certain areas may appear to be transitional between two types. The relative expected variation within a type is of similar magnitude to the variation within a given forest type. Furthermore, humus layers, like forest types, are profoundly influenced by fires, cutting, etc., and redevelopment of a mature humus layer after a major disturbance usually requires a long time.

It is hoped that the foregoing classification and description of the forest humus layers will serve as a valuable aid to soil scientists and foresters who are interested in soil-tree relationships. Because of their apparent importance, the humus layers deserve particular attention. Observations in the northeastern United States have indicated that, in general, mulls are more productive than mors. Certain species reproduce better on mor; and others, better on mull. A ground fire behaves quite differently in a coarse mull and in a greasy mor. The greater part of the roots of trees are often confined to the humus layer. The environment which surrounds these roots is extremely important in determining the welfare of the trees on the site. It is not asserted that the humus layers are all-important, but it would seem that because of their relation to organic matter, biological activity, aeration, water infiltration, water-holding properties, and root content, the qualities of the humus layers are criteria essential to the classification of forest lands (3).

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PLATE 1

FIG. 1. Representative material from an F layer beneath a mixed hardwood stand in central New York State.

FIG. 2. H-layer material from the same stand as that of figure 1.

FIG. 3. Coarse mull humus layer developed on Crosby silt loam soil in Ohio.

FIG. 4. Coarse mull soil is friable and porous.

FIG. 5. Comparative size of granules in (left to right) coarse, medium, and fine mulls.

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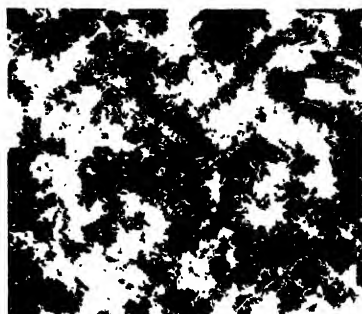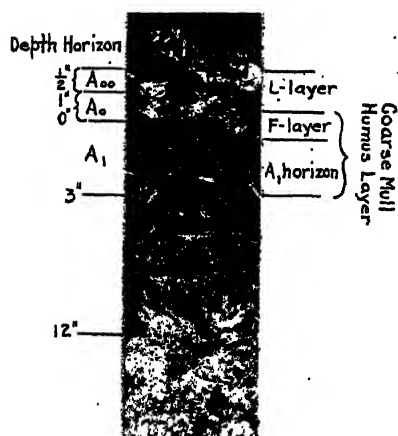
FIG. 1

FIG. 2

FIG. 3

FIG. 4
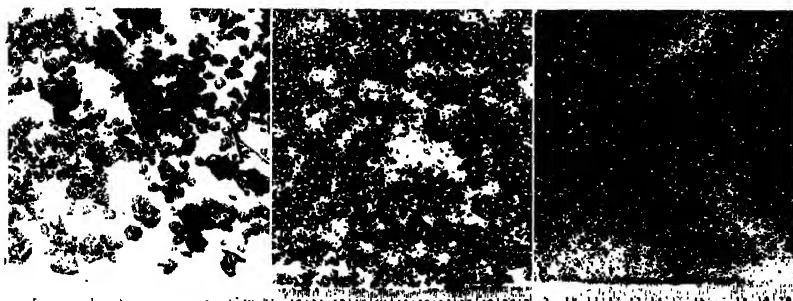
FIG. 5

PLATE 2

FIG. 1. A typical fine mull humus layer developed beneath a stand of sugar maple, basswood, white ash, yellow birch, and beech in the Pack Forest, Warrensburg, New York.

FIG. 2. A firm mull developed in a grazed woodlot in Ohio.

FIG. 3. A typical twin mull developed beneath a mixed hardwood stand on Volusia slit loam soil in Central New York.

FIG. 4. A matted mor humus layer developed on Muskingum silt loam soil in Ohio.

FIG. 5. Note how a matted mor humus layer is held together by roots.

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Fig. 1

Fig. 2

Fig. 3

Fig. 4

PLATE 3

FIG. 1. A granular mor humus layer beneath a spruce hardwood stand in the Adirondacks.

FIG. 2. Greasy mor humus layer from the Pack Forest, Warrensburg, New York. The forest stand consists of hemlock with an admixture of large white pine.

FIG. 3. Fibrous mor humus layer developed beneath a stand of pure hemlock. Note the felty appearance of the H-layer.

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Depth Horizon

2"	A_{oo}	L-layer
6"	A_o	F-layer
		H-layer
0"		A_2 horizon
3"	A_2	B_2 horizon
	B_2	
7"	B_3	B_3 horizon
13"		
	C	C horizon
18"		

Granular Mor Humus Layer

FIG. 1

Depth Horizon

1"	A_{oo}	L-layer
3"	A_o	F-layer
		H-layer
0"	A_2	A_2 horizon
1"		B_2 horizon
	B_2	
4"	B_3	B_3 horizon
9"		

Greasy mor humus layer

FIG. 2

½"	A_{oo}	L-layer
4"	A_o	F-layer
		H-layer
0"	A_2	A_2 horizon
2"		B_2 horizon
	B_2	

Fibrous mor humus layer
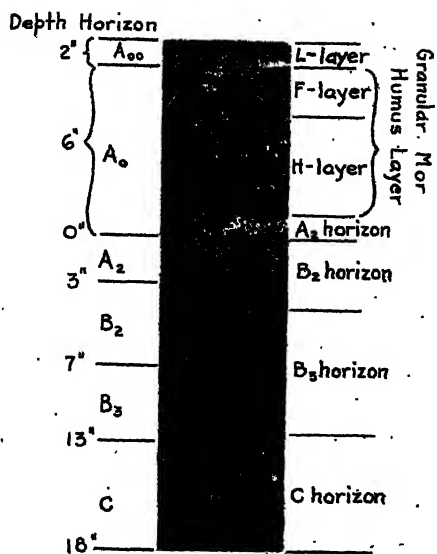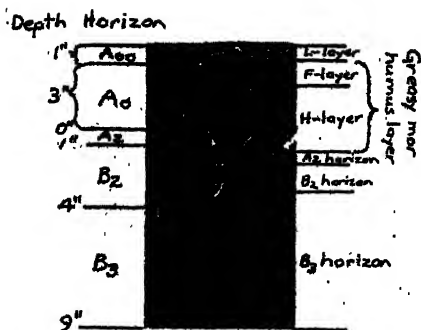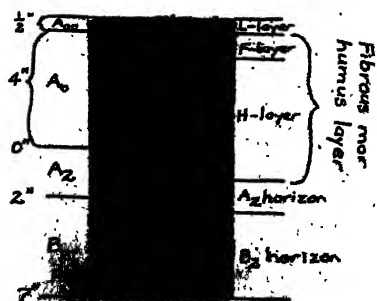
FIG. 3

FACTORS INFLUENCING THE AVAILABILITY OF THE INDIGENOUS PHOSPHORUS IN AN ACID TROPICAL SOIL

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Decomposable organic matter is known to be important to crop yields because of its assistance in supplying the growing crop with nutrients from the soil. Although in some cases the chief mechanism of such assistance has been discovered by research—for instance the function of carbon dioxide, released from organic residues, in influencing the availability of the indigenous phosphorus in calcareous soils (4, 5)—, much remains to be learned in this respect, especially regarding tropical soils. In this paper an attempt is made to demonstrate the importance of crop residues in influencing the availability of the indigenous phosphorus in a Java soil of rather low silica-sesquioxide[1] ratio, acid through long-continued cropping.

The author in his agronomic research work on sisal fiber (*Agave sisalina* Perrine) and on tapioca[2] starch (*Manihot utilissima* Pohl) incidentally came across some instances in which there was a direct indication of the aforementioned importance (2). On the basis of the evidence thus obtained, some field experiments were laid out with a view to specifying this evidence in the soil concerned.

CHARACTERIZATION OF THE EXPERIMENTAL SOIL

The soil on which the experiments were made occupies stretches in the northern coastal plain of West Java. It is a deep, red loam clay of volcanic origin, probably deposited in the form of volcanic-mud streams during remote times of the Quarternary period. Its Al_2O_8 and Fe_2O_8 contents are 25 and 15 per cent respectively, and its molecular silica-sesquioxide ratio, which varies in places, is around 2. Its base-exchange capacity is 30 m.e. per 100 gm. of soil, on an oven-dry basis. When the soil is covered with natural forest, its pH varies in different localities between approximately 6 and 7. After the land is cleared, the pH falls by base exhaustion through cropping for 10 to 20 years to a rather constant level, varying in different places from approximately 4.5 to 5.5.

The rainfall of the area concerned is about 2000 mm. per annum. It is

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[1] Silica and sesquioxides of total soil.

[2] This is the name used for the plant by English-speaking people in Java, the Dutch designation being "cassave." The name "manioc," common in French colonies, is not used in Java.

distributed very unevenly between a wet monsoon, from December to March inclusive, and a dry season from June to September inclusive, with intervening transitional periods. The temperature, which varies comparatively little seasonally, averages 27°C., the variation between approximately 20° and 37°C. being chiefly due to fluctuations between day and night temperatures.

The virgin soil is covered with a rather heavy forest, having a thick undergrowth, resulting in an organic matter content in the upper layers, varying according to locality, of approximately 3.5 to 4.5 per cent with a C/N ratio of about 13. Clearing and cultivation of the land initiates a decrease in organic matter content, which proceeds under exhausting conditions to about 1.5 per cent, the C/N ratio meanwhile being narrowed a little.

The earliest sisal planted in this area was an experiment, laid out in 1919, in a place which had already been nearly exhausted by native crops, such as rice, maize, and peanuts, all grown without irrigation. No forest area of this soil has yet been completely exhausted by sisal, though sisal experiments have been carried out in this soil in localities that had already been exhausted to various degrees previously by the native crops. These experiments allow of the following estimations of sisal yield in respect to soil exhaustion.

If, as in actual practice, all the sisal leaf produced is removed, the stumps being worked into the soil after every sisal cycle[3], this soil, as freshly cleared of forest, is estimated to be capable of sustaining, without additional fertilization, three consecutive sisal cycles lasting together about 22 years, with a combined yield of about 1400 tons of fresh leaf per hectare. During the third cycle the sisal exhibits signs of severe potassium deficiency in the form of necrotic patches of varying size, spreading upward from the base of the leaf, i.e., from the vicinity of its meristematic tissues. A fourth sisal cycle is physiologically impossible without fertilization. If after the exhaustion described, however, the soil is fertilized with potassium salts only, it can bear at least two more sisal cycles, lasting together about 14 years, with a combined yield of about 1100 tons of fresh leaf per hectare.

The indigenous potassium extracted from the soil by the sisal during the first three cycles is estimated, under the given conditions, at about 3.7 tons K_2O per hectare. At the end of the fifth cycle the indigenous phosphorus and nitrogen[4] are not yet depleted, but the reserves in the soil can be measured only by continuing the present experimental system. The quantities extracted by the sisal from the soil during the five cycles described are estimated at about 1.4 tons P_2O_5 and about 4.1 tons N per hectare.

[3] The term "sisal cycle" is used in this paper to designate the total life of a sisal field from planting to conversion into a new sisal or other field, which in Java usually lasts from 7 to 9 years. A "tapioca cycle" is similar, though its duration is much shorter, viz., in the case of starch production usually from 16 to 20 months.

[4] The concept "indigenous nitrogen," as used in this paper, may include nitrogen assimilated from the air by soil microorganisms.

CROPPING HISTORY OF THE EXPERIMENTAL AREA

The forest cover was cleared 80 or more years ago. The soil potassium was depleted by growth of the aforementioned native crops for 50 or more years without fertilization. Then the land was left in pasture for native cattle, which were taken off at night. Thus much of the cattle excreta was withheld from the grazing area. The land thus treated carried a close but poor grass cover. Consequently, although the soil was reenriched with organic matter, the enrichment with available potassium by the natural soil processes was very slow.

Field experiment S.93 was laid out in January, 1928, on such land, which for 11 years had been under the grazing system described. Of its 32 plots, 16 were kept fallow and were clean-weeded during the first year, while the other 16 carried a green manure cover of *Tephrosia candida* D.C. After one year the green manure cover of 8 of the latter plots was worked into their own soil, whereas the green manure tops from the other 8 were worked into the soil of 8 of the fallow plots.

The effects of the various green manure treatments on fiber yield of the sisal, following the green manure period, were evident, though small in comparison with those of the fertilizer treatments applied to the sisal (1). Within the latter treatments, all of which contained potassium, the effects of nitrogen, phosphorus, magnesium, and calcium were negligible in comparison with that of potassium.

Because of their relative smallness, the green manure treatments will henceforth be disregarded. The term "effect of a fertilizer treatment" in S.93, will actually refer to main effects in view of green manure treatments, unless otherwise indicated.

Of the six fertilizer treatments of S.93, only four are relevant to the present purpose, viz.: "unfertilized," "potassium only," "NPKMgCa," and "N-KMgCa," covering 16, 8, 2, and 2 plots respectively.

The sisal grew well on the unfertilized plots during its first year but began to exhibit signs of potassium deficiency half a year later. As compared with normal growth, the fiber yield began to decline visibly on these plots when the sisal was only $2\frac{1}{2}$ years old. The plants never reached the flowering stage[5] and 46 per cent of them died without having poled during the course of the experiment, which lasted 6 years and 10 months. At the end of the experiment the fiber yield amounted to 7.03 tons per hectare on these plots, against 20.20 on the potassium-only plots.[6] This difference of 13.17 tons of sisal fiber represents more than 200 kgm. P_2O_5 in the harvested sisal leaves and the sisal

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[5] In sisal, only one growing point produces normal leaves. When this begins to form a flowering pole, the production of normal leaves stops and the plant dies within a year.

[6] At the end of the experiment the plants of the potassium-only plots had formed flowering poles in 68 per cent of their original number, which had been 5640 per hectare.

stumps, the latter having been eliminated from the plots of the experiment. This quantity of P_2O_5 may be estimated under the given circumstances as equivalent to more than 200 tons of total fresh tapioca yield.[7] The N/P ratio in the total fresh tapioca yield does not usually differ much from that in the pooled sisal leaves and stumps under equal feeding conditions. Thus said quantity of N, corresponding to the 13.17 tons of sisal fiber, represents at least 200 tons of total fresh tapioca yield. How much of this nitrogen had been assimilated from the air by soil microorganisms during the course of the sisal experiment, however, is not known.

After the sisal experiment the sisal stumps and other organic remnants were eliminated from the plots as completely as possible. The soil was left fallow for about 13 months. No weeds came up in the unfertilized plots. After the period of fallow, that is, in January, 1937, the soil of the unfertilized plots was cultivated in the usual way to eliminate as many as possible of the coarse roots and other coarse organic remnants.

These plots were then transformed into an NPK tapioca experiment of factorial design, with a view to replanting the latter without additional fertilization as many consecutive times as might appear desirable. So far the plots have been planted once with fertilization and twice without. From each of the first two plantings, the first designated as "T.503" and the second as "T.503 (cont.)," a crop has been harvested.

LAY-OUT OF TAPIOCA EXPERIMENTS

The first of the tapioca cycles was planted in January, 1937, and lasted 15 months. Its fresh tuber and dry starch yields have been published to demonstrate the use of "factorial diagrams" (3). The second cycle was planted in April, 1938, immediately after the first, and was kept in the soil for 18 months.

Each plot of the tapioca experiments consists of three rows of nine plants with a spacing of 3 by 3 English feet. Each plot has been surrounded by sheets of bamboo matting, standing on edge and deeply embedded in the soil, with a view to preventing sheet erosion under the system of clean cultivation employed. In estimating yields the 20 marginal plants per plot were discarded.

The fertilizer treatments were the 36 factorial combinations of the nitrogen levels, per plant, of 0, 12, 24, and 48 gm. of sulfate of ammonia containing 21 per cent N; the phosphorus levels, per plant, of 0, 12, and 24 gm. double superphosphate containing 36 per cent P_2O_5; and the potassium levels, per plant, of 0, 36, and 72 gm. potassium sulfate containing 48 per cent K_2O. The fertilizers were mixed and then applied in holes 10 cm. deep, three around each tapioca cutting at a distance of 20 cm. from the latter, 2 weeks after planting, when all the cuttings had begun to form shoots.

There was no room for plot replication, and all the treatments were randomized over the whole area of the unfertilized plots of S.93.

[7] Comprising fresh tubers, fresh stems, and fresh leaves, the last mentioned not including those shed before harvesting.

ESSENTIAL CONCEPTS REGARDING THE AVAILABILITY[8] OF PLANT NUTRIENTS

The concept "extractable" refers to an equilibrium between the power of a given plant species to extract a given plant nutrient from a given soil under given conditions of time and weather. Within these limitations the extractable quantity of a given indigenous plant nutrient depends on, first, the quantity of that plant nutrient in the "available" state and, second, the available quantities of the other plant nutrients. If one or more of the latter quantities are too small to allow maximum extraction of the first, suitable experimentation with the aid of fertilizers can eliminate that shortage.

The maximum "extractable" quantity thus having been determined, the corresponding "available" quantity still cannot be computed, since the equilibrium function between "extractable" and "available" is not known. If, as in the present case, however, a second-cycle maximum of extractability of a given plant nutrient is subtracted from the corresponding first-cycle maximum, the unextractable remainder is eliminated from the difference. Since it is known that in the Java soil under consideration, no nutrient factors other than nitrogen, phosphorus, and potassium are of importance in limiting tapioca yield, it is possible to evaluate by suitable experimentation the three corresponding differences, from which the unextractable remainders of available indigenous nitrogen, phosphorus, and potassium respectively, have been eliminated. These differences can be expressed, not only in terms of chemical units, but also in terms of yield.

"YIELD" AS A CRITERION OF AVAILABILITY

"Yield," a criterion of availability, is defined as the combined fresh weight per hectare of the tubers,[9] the stems, and the leaves still on the stems at the time of harvesting the tapioca. The exclusion of the roots proper from this definition leaves it somewhat incomplete, but it would be extremely difficult to estimate the weight of the roots proper, because tapioca roots are very fragile and consequently only detachable with great difficulty from the clayey soil of the experiment. It would not be too difficult to estimate the fresh weight of the leaves shed before harvesting. Neither would it be too difficult to remove regularly the shed leaves from the plots in order to prevent the return of plant nutrients to the growing crop, which otherwise might take place by way of the soil after the decay of the leaves. It would not be possible, however, to prevent the return of plant nutrients from old leaves into the growing crop before their shedding. Thus shed leaves have not been included in the criterion "yield."

"Yield," as defined, will be referred to henceforth as "tapioca yield" or simply as "yield," wherever no misunderstanding can result.

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[8] The terms "available" and "extractable," as used in this paper, refer to indigenous plant nutrients, unless explicitly stated otherwise.

[9] Tapioca tubers are morphologically parts of the root system.

PLANT-FOOD RESERVES

The term "reserves" will be used in this paper in reference to the indigenous plant food only, whereas remnants of fertilizer plant food, applied to a previous crop will be referred to as "residues."

"Plant-food reserves," at a given moment during the experiments, are defined as those quantities of indigenous plant food which were or could become available to sisal or tapioca at that moment or later until the end

TABLE 1

Yields, in tons per hectare, in T.503 and T.503 (cont.)*

TREATMENTS	YIELDS		TREATMENTS	YIELDS	
NPK	T.503	T.503 (cont.)	NPK	T.503	T.503 (cont.)
000	14.6	22.2	200	12.0	13.2
001	8.6	47.4	201	24.9	41.9
002	25.7	55.2	202	22.3	47.2
010	17.2	10.8	210	14.6	22.5
011	51.5	42.2	211	48.9	45.3
012	37.8	46.8	212	42.0	42.8
020	11.7	21.6	220	18.9	17.1
021	62.6	37.1	221	74.6	34.7
022	57.5	51.8	222	78.0	110.0
100	23.2	20.1	400	18.0	13.0
101	24.9	37.1	401	24.9	50.3
102	22.3	39.4	402	12.0	57.9
110	8.2	23.1	410	6.5	21.6
111	61.8	36.8	411	61.8	37.4
112	62.6	73.0	412	40.3	68.0
120	19.7	20.1	420	14.6	13.7
121	54.9	46.4	421	85.8	24.5
122	61.8	89.8	422	97.0	77.5

* T.503 = first tapioca cycle; T.503 (cont.) = second tapioca cycle.

of T. 503 (cont.), under the conditions considered. In the case of nitrogen, the quantity thus defined may include nitrogen assimilated from the air by soil microorganisms. According to this definition, the potassium reserves, at the end of the sisal experiment, were very small in the unfertilized plots of S. 93, and thus in the whole area of the future T. 503 and T. 503 (cont.). The corresponding phosphorus and nitrogen reserves were considerably greater, viz., by the equivalent of more than 200 tons of tapioca yield per hectare, as explained in a foregoing section.

GRAPHICAL REPRESENTATION OF THE EXPERIMENTAL EVIDENCE

The yields of the two tapioca cycles are specified in table 1 together with the corresponding treatment formulas. In these formulas the first number indicates nitrogen, the second phosphorus, and the third potassium. The value of the numbers denotes the relative strength of the corresponding factors. Thus, 412 denotes the treatment combination of the quadruple nitrogen, the single phosphorus, and the double potassium level, corresponding to a fertilizer
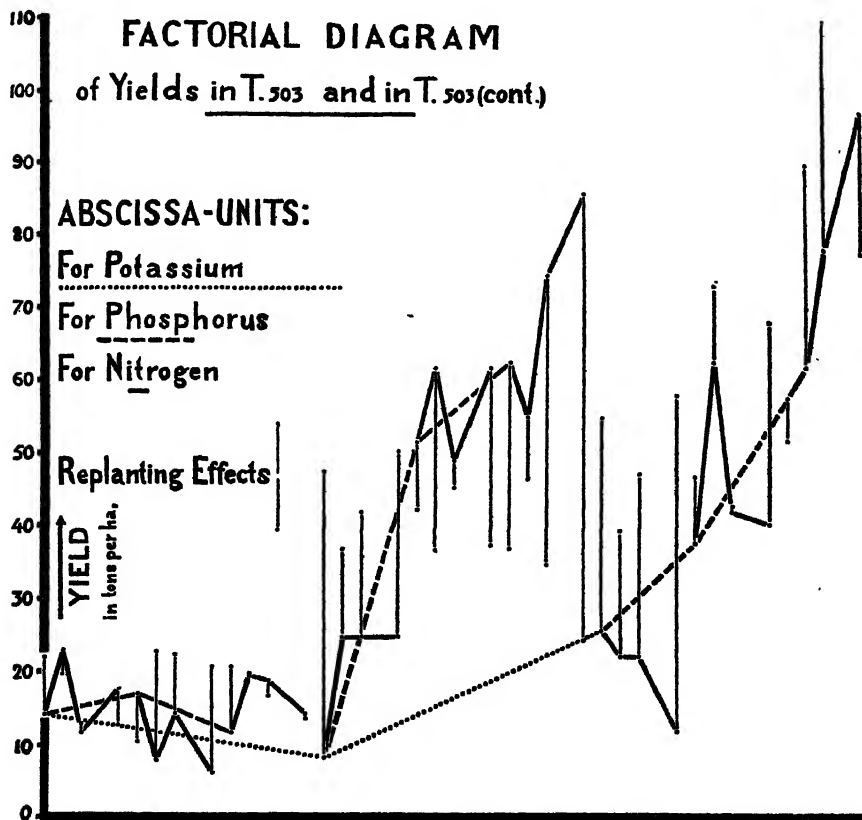
FIG. 1

application of the following mixture: 48 gm. sulfate of ammonia, 12 gm. double superphosphate, and 72 gm. potassium sulfate. Wherever the value is not zero, the word "dose" can be substituted for the word "level." In the afore-mentioned mixture, for example, the 48 gm. of sulfate of ammonia may be called not only "the quadruple nitrogen level" but also "the quadruple nitrogen dose."

The data of table 1 have been represented graphically in a five-dimensional

"factorial diagram" with yield as the dependent, against nitrogen, phosphorus, potassium, and "replanting of the tapioca" as the four independent variables.

Although the structure of "factorial diagrams" has been discussed in an earlier paper (3), it seems desirable to explain in some detail the construction of the present diagram and some of its characteristics.

In the diagram the vertical lines belong exclusively to the second cycle; all the others, to the first. To begin with, the vertical lines will not be considered, that is, only the first cycle will be discussed.

The dotted line of the diagram contains three points representing the yields of the potassium-only treatments. It is the regression line of yield with potassium-only and is called the "K-line." Its abscissa unit is indicated in the legend of the diagram. The K-line can be considered as the diagram for the factorial design consisting only of the K-factor at three levels.

In constructing the NPK-design in table 1, each of the three K-levels has been combined with each of the three P-levels. Correspondingly the diagram contains three P-lines, which originate from the three points of the K-line. Each point of the P-lines represents the yield of the corresponding PK-treatment. The abscissa unit for the phosphorus levels, as indicated, is much shorter than that of the K-line in order to prevent undue intersecting of diagram lines. The three P-lines together with the K-line form the diagram for the factorial design of the two factors phosphorus and potassium, each at three levels. The slopes of the P-lines represent the regressions of yield on phosphorus in the absence and in the presence of potassium. In respect of regression the three P-lines are comparable with one another but not with the K-line. It is apparent that the second and third P-lines are far steeper than the first; in other words, whereas the yield effects of the P-levels are negligible in the absence of potassium, they are large in the presence of the latter and vice versa. In statistical terms it may be said that the interactions between phosphorus and potassium are large; furthermore that they increase with increasing P-level but decrease somewhat with increasing K-level. Meanwhile, the fact should not be overlooked that the PK-interactions considered thus far are those of the two-factor PK-design and not those of the complete NPK-design, since thus far nitrogen has not been taken into consideration.

In further constructing the complete NPK-design in table 1 each of the nine PK-combinations considered thus far has been combined with each of the four N-levels. Correspondingly the diagram contains nine N-lines, originating from the nine points of the PK-diagram. Each point of the N-lines represents the yield of the corresponding NPK-treatment. The regressions of the N-lines are comparable with one another but not with those of the P-lines or with that of the K-line.

The N-lines are most naturally divided into three groups, each group consisting of the three branches of a P-line. It is readily seen that little regression occurs in the three N-lines of the first group, whereas the N-lines of the two other groups exhibit, in general, increasing regressions as the P-levels from

which they originate increase. In other words, nitrogen is very slightly effective in the absence of either phosphorus or potassium or both; but it is effective if both are present, and the higher the P-level, the greater is the effectiveness. An increase in K-level increases somewhat the former effectiveness, since the two highest N-lines of the third P-line are somewhat steeper than the corresponding N-lines of the second P-line. Expressing these features in the usual statistical terms, it may be said that the NPK-interactions are, on the average, of some importance, and they increase with increasing P-levels and also somewhat with increasing K-levels.

The interactions of the foregoing two-factor PK-design can now be complemented for N, as within the full NPK-design. To do this, the nine points of the two-factor PK-design have only to be replaced by the mean[10] values of the corresponding nine N-lines. From the resulting diagram, which, on account of elimination of the N-lines, contains only nine points, the PK-interactions of the NPK-design can readily be deduced or visually estimated. In a similar way a twelve-point diagram can be deduced from the NPK-diagram by elimination of the P-lines. From such a diagram the NK-interactions of the NPK-design can be deduced or visually estimated. Also the NP-interactions of the NPK-design can readily be studied in a similar way by elimination of the K-line. The main effects for N, P, and K, which are four- or three-point lines respectively, can easily be derived from the twelve- and nine-point diagrams by elimination of one further factor from each.

The end points of the vertical lines in the diagram represent the plot yields of the second cycle. Thus the lengths of the vertical lines show the differences between the second- and first-cycle yields on identical plots. The vertical lines ascend if the yields of the identical plots are larger in the second than in the first cycle; they descend if the reverse is true. An appropriate name for the vertical lines is "replanting effects," as will be explained later.

The fertilizer levels of the second cycle equal the fertilizer residues left in the plots, because they were not extracted by the tapioca of the first cycle. The yield effects in the first cycle varied largely within those treatments which were equal with respect to any of the N-, P-, or K-levels. Thus in the plots that received identical N, P, or K doses at the beginning of the first cycle, the unextracted residues of these initially equal doses must have been very unequal at the beginning of the second cycle. Because most of the fertilizer residues can be estimated only very roughly from the first-cycle yields, no attempt has been made to construct a separate second-cycle diagram to show the proper regressions of the N-, P-, and K-lines. It is for this reason that the second-cycle yield effects, more aptly termed the "replanting effects," have been drawn in the diagram as vertical lines, thus leaving the second-cycle regressions a blank.

An exception to the foregoing remark regarding insufficient knowledge of

[10] Taking into account the fact that the fourth N-level is twice the third, and four times the second.

the fertilizer residues is presented by the first third of the diagram, since the corresponding treatments had negligible effects in the first cycle, whence the fertilizer residues in the plots concerned must have been about equal to the original treatments.   It follows that for this part of the diagram, regressions may be computed for the second cycle as for the first.   The same assumption has been considered to be valid for the treatments of the fourth and the seventh N-line, which contained no phosphorus combined with potassium.   It is not difficult to read from the diagram those second-cycle N-lines which correspond with these first to fourth and seventh N-lines.   One has only to imagine the end points of the four vertical lines that originate from each of these N-lines as connected by a solid line.

All the "replanting effects" of the fifth and sixth N-lines are negative, and they descend farther, the higher was the plot yield in the first cycle.   The highest of these plot yields in the first cycle corresponds with a yield in the second cycle which equals approximately the yield of the 000-treatment in the same cycle.   This fact should be interpreted thus: the single K-dose, as applied in the plot concerned, was consumed entirely by the tapioca grown on that plot during the first cycle.   This was apparently made possible because the plot received, besides the single K-dose, also the double P-dose and the quadruple N-dose.   Apparently, in this plot, the K-residue was zero.

The plot of the end point of the ninth N-line receives the same P- and N-application, but twice as much potassium, as the plot just discussed.   Accordingly its K-residue must have been considerable, since the two plots differed little in first-cycle yield.   Actually its second-cycle yield was very much larger than that of the other plot, as evidenced by the diagram.

DEFINITION OF "EFFECTS"

In this paper, the term "factor," as applied to plant food, refers to fertilizer and not to indigenous plant food.   Likewise, the term "effect," as applied to plant food, refers exclusively to fertilizer.

The effect of a factor level or combination of factor levels within a treatment is defined here as the yield of that treatment minus the yield of a treatment differing only in the absence of said factor level or combination of factor levels. It follows that the effect of a treatment is defined as the yield of said treatment less that of the 000-treatment.   Furthermore, the yield differences within treatments between the two tapioca cycles may be termed, according to the foregoing definition, "replanting effects," the second cycle having been planted on the same plots as the first cycle.

THE YIELD MAXIMA ATTAINABLE WITH THE INDIGENOUS POTASSIUM IN T. 503 AND T. 503 (CONT.)

The yield maxima attainable with the indigenous potassium have to be estimated from the yields of plots not fertilized with potassium, that is, from the yields of the first to third nitrogen lines.   It is evident from the diagram that

with or without phosphorus and/or nitrogen fertilization these yields were very low in both cycles.

The only evident positive effects within the potassium-free treatments are afforded by the second-cycle yields of the sixth to eighth treatments, which combine nitrogen with the single phosphorus dose. The mean of the corresponding nitrogen effects equals +11.6 tons and is statistically very significant (table 2, No. 1). Furthermore, a negative regression[11] of yield on nitrogen occurs clearly within each of the first and third nitrogen lines of the second cycle. Its pooled value equals −2.2 tons per single nitrogen dose and is statistically significant (table 2, No. 2). No further statistically significant variation, ascribable to variables, occurs within the first three nitrogen lines

TABLE 2

Tests of significance of yields, referred to in text

NUMBER	MEAN	REGRESSION	t	
1	+11.60		26.606	Against 9.925 in its 1 per cent level of significance
2		−2.2171	3.514	Against 3.365 in its 2 per cent level of significance
3		−1.2753	4.723	Against 4.587 in its 0.1 per cent level of significance
4	+6.60		2.056	Against 2.365 in its 5 per cent level of significance
5	+29.98		10.541	Against 4.587 in its 0.1 per cent level of significance
6		+5.2818	6.075	Against 5.841 in its 1 per cent level of significance
7	+23.80		4.094	Against 3.182 in its 5 per cent level of significance
8	−9.90		4.506	Against 3.182 in its 5 per cent level of significance
9	+5.75		4.485	Against 3.182 in its 5 per cent level of significance

of the second cycle. Consequently, the second-cycle yield maximum, attainable with the indigenous potassium, should be estimated at the mean second-cycle yield of the first, sixth to eighth, and ninth treatments, i.e., at the mean of the highest five second-cycle yields.

No statistically significant variation ascribable to variables occurs within the first three nitrogen lines of the first cycle. A strong, highly significant (table 2, No. 3) negative regression of the replanting effects concerned on yield of the first cycle does occur, however, amounting for the pooled first three nitrogen lines to −1.3 tons per ton of first-cycle yield. This is explained by the assumption that the higher the first-cycle yields, the smaller were the

[11] In connection with the term "regression," plant food names will be used in reference to fertilizer nutrients only.

remainders of the available indigenous potassium. Consequently, it would be entirely wrong to estimate the first-cycle yield maximum attainable with the indigenous potassium at the mean first-cycle yields of the same five treatments, the second-cycle yields of which served to estimate the corresponding second-cycle yield maximum. The former maximum yield may be estimated, although narrowly, at the mean first-cycle yield of the seven remaining treatments, or more properly at the mean of the five highest yields within these seven.

Accordingly, the yield maxima attainable with the indigenous potassium are estimated at 22.2 tons for the second cycle and at 19.4 or narrowly at 17.7 tons for the first.

THE YIELD MAXIMA ATTAINABLE WITH THE INDIGENOUS PHOSPHORUS IN T. 503 AND T. 503 (CONT.)

The yield maxima attainable with the indigenous phosphorus have to be estimated from the yields of the first, fourth, and seventh nitrogen lines.

It is apparent from the diagram that no significant variation occurs between the mean yields of these three lines within the first cycle. If the first-yield points of each of these lines are discarded, the mean of the three remaining yields of the fourth nitrogen line is 6.6 tons higher than that of the six other yields. Although this difference is not statistically significant (table 2, No. 4), the present first-cycle maximum is estimated at the mean of these three yields in order to prevent its underestimation. It equals 24.9 tons.

Within the second cycle the mean of the pooled yields of the fourth and seventh nitrogen lines is 30 tons higher than that of the first nitrogen line. This difference is statistically very significant (table 2, No. 5). Furthermore, if the treatments without nitrogen are discarded, an evident positive regression of yield on nitrogen occurs within the remaining parts of each of these lines. This amounts to $+5.3$ tons per single nitrogen dose and is statistically very significant (table 2, No. 6). Consequently, the present second-cycle maximum is estimated at the mean of the four highest yields of the fourth and seventh nitrogen lines, i.e., at 52.7 tons.

THE YIELD MAXIMA ATTAINABLE WITH THE INDIGENOUS NITROGEN IN T. 503 AND T. 503 (CONT.)

The yield maxima attainable with the indigenous nitrogen have to be estimated from the three phosphorus lines. It is evident from the diagram that only the second and third of these lines need be considered for the present purpose.

Within the first cycle the course of the second phosphorus line suggests the reaching of a maximum, but that of the third, a continuation of the positive regression of yield on phosphorus, beyond the phosphorus levels applied. In both cases, however, there occurs beyond the phosphorus line a strong nitrogen effect, which reveals that within the end points of both lines the availability

of the indigenous nitrogen must have been near its limit of extractability. The mean nitrogen effect within the four treatments corresponding with the four highest first-cycle yield points, i.e., that of the two strongest nitrogen doses within each of the sixth and eighth first-cycle nitrogen lines, equals 23.8 tons, and is statistically significant (table 2, No. 7). Consequently, the best estimate for the present first-cycle maximum lies in the neighborhood of the end points of the second and third phosphorus lines. It is estimated liberally at 62.6 and narrowly at 57.5 tons.

Within the second cycle, the second phosphorus line exhibits a clear maximum at 42.2 tons, which may be due to shortage of fertilizer residues. The course of the third suggests the reaching of a maximum near its end point. The yield at this point is 51.8 tons, which is 5.7 tons lower than that of the corresponding first-cycle point. It is consistent with this decrease in yield from the first to the second cycle that in the latter the mean nitrogen effect within the ninth nitrogen line is 19.2 tons greater than in the former.

TABLE 3

Yield maxima, in tons per hectare, within T.503 and T.503 (cont.)

	YIELD MAXIMA* ATTAINABLE WITH		
	Indigenous potassium	Indigenous phosphorus	Indigenous nitrogen
T.503.......................... {	19.4	24.9(+)	62.6(+)
	17.7(−)		57.5(−)
T.503 (cont.)......................	22.2	52.7	51.8
Differences.....................	+4.5 to +2.8	+27.8	−5.7 to −10.8

* (+) indicates a liberal estimation; (−), a narrow estimation.

IMPROVEMENT IN THE AVAILABILITY STATUS OF THE INDIGENOUS PHOSPHORUS FROM T. 503 TO T. 503 (CONT.)

The yield maxima estimated in the three foregoing sections are summarized in table 3. In terms of tapioca yield, they are estimates of the maximum quantities of the available indigenous potassium, phosphorus, and nitrogen respectively, which can be extracted by tapioca from the variously fertilized experimental plots under the given circumstances of cycle succession, cycle lengths, and weather.

From the first to the second cycle the range of these values of maximum extractability decreased from a narrow estimate of 38.1 tons to 30.5 tons, i.e., by at least 20 per cent of the first-cycle range, even without taking into account the fact that the second cycle was 3 months longer than the first. This feature is consistent with the corresponding expectation from a soil in the course of exhaustion.

Table 3 shows the differences between the values of maximum extractability

within the nutrients. It follows from the previous discussions that these differences express in terms of yield the differences between the maximum quantities of the available potassium, phosphorus, and nitrogen, respectively, that occurred in the differently fertilized plots during the first and the second cycle.

Apparently, the maximum quantity of the available indigenous potassium in T. 503 (cont.) was a little greater than that in T. 503. The cause of this difference cannot be discovered with certainty. It may be, at least partly, the longer growing period of the former experiment, which exceeded that of the latter by 3 months, or by 20 per cent of the first-cycle period.

On the other hand, the maximum quantity of the available indigenous nitrogen in T. 503 (cont.) decreased a little from that in T. 503, notwithstanding the longer cycle of the former experiment. This decrease is consistent with the normal expectation from a soil in the course of exhaustion.

The most conspicuous feature of the differences in table 3 is the extraordinary increase in the maximum quantity of the available indigenous phosphorus from the first to the second cycle, equalling at least +27.8 tons. Even when corrected by one sixth of its value, to +23.2 tons, to compensate for the extra length of the second cycle, this difference is statistically very significant, since the fiducial upper limit for the 0.1 per cent level of significance equals +19.2 tons. The only explanation of this feature seems to be the assumption that the availability status of the indigenous phosphorus within the plots has considerably improved from the first to the second cycle.

Though it was known from the sisal experiment, S. 93, which preceded T. 503, that the phosphorus reserves of the soil of T. 503 were considerable, as compared with its small potassium reserves, it appears from table 3 that its maximum quantity of extractable indigenous phosphorus was only a little greater than the corresponding quantity of potassium. In other words, its considerable phosphorus reserves were hardly effective during the first cycle, but became much more effective afterward within some of the fertilizer treatments

CAUSE OF THE LOW-AVAILABILITY STATUS OF THE INDIGENOUS PHOSPHORUS IN T. 503

In S. 93 the yield of fiber was only a little higher for the NPKMgCa than for the N—KMgCa treatment during the entire course of the sisal cycle [as may be seen from the two upper rows of table 1 in (2)]. Furthermore, the yields of the potassium-only treatment were not much lower than those of the N—KMgCa treatment during the entire course of S. 93 (2). Thus it may be inferred that at the beginning of S. 93, i.e., after a grazing period of 11 years when the soil bore a poor but close grass cover, the availability of the indigenous phosphorus was considerable and this availability was maintained during the entire sisal cycle of 6 years and 10 months, if the soil was regularly fertilized with potassium. On the other hand, it has been shown that the phosphorus availability was poor in T. 503 and thus certainly at the end of S. 93 in the

unfertilized plots of the latter. Consequently, the low availability of the indigenous phosphorus had been caused by growing sisal during 6 years and 10 months without potassium fertilization, whereas the soil had become potassium-deficient after only about $1\frac{1}{2}$ years of sisal growth.

Since this inference rests partly on experimental evidence obtained with sisal, i.e., evidence of an indirect nature regarding tapioca, and since, furthermore, it does not allow of definite statistical analysis, its confirmation by direct experimental evidence, obtained with tapioca, is desirable.

Such evidence was afforded by tapioca, grown at the same time as that of T. 503, on those plots of S. 93 which had during the course of S. 93 been fertilized with potassium alone, whereas T. 503 had been planted on the unfertilized plots of S. 93. In the K-fertilized plots of S. 93, the considerable availability of the indigenous phosphorus, maintained during the entire course of the sisal cycle, ought to be demonstrable by comparatively high yields of the

TABLE 4

Effects, in tons per hectare, of the single phosphorus dose within T.508 (partim)

TREATMENTS		EFFECTS		YIELDS OF TREATMENTS WITHOUT PHOSPHORUS	
NPK	NPK	Block 1	Block 2	Block 1	Block 2
211	201	+4.2	+33.4	60.9	30.9
011	001	−7.8	0.0	48.9	29.1
210	200	+2.4	+24.0	53.3	32.6
010	000	+20.6	+0.9	31.7	30.0
Mean phosphorus effect............		+9.71			
Mean yield without phosphorus.....				39.68	
Mean yield with phosphorus........			49.39		

succeeding tapioca in the identical soil without the application of phosphorus fertilizer.

On the fertilized plots of S. 93, T. 508 was planted to tapioca 3 months later than T. 503, with which it was harvested simultaneously. These plots of T. 508 which were planted on the potassium-only plots of S. 93 will be referred to as "T. 508 (partim)."[12] They are the only part of T. 508 relevant to the present discussion. Within each of the two blocks of T. 508 (partim) a 2^3 NPK factorial design had been randomized with the components of the two T. 503 treatments 000 and 211 as levels. The yields and the phosphorus effects of T. 508 (partim) are shown in table 4.

Formally, the phosphorus effects within T. 508 (partim) should be compared with the identically denoted T. 503 effects of treatments containing potassium, i.e., with the effects of 211–201 and 011–001, only. Since no

[12] With the exceptions to be mentioned, T.508 (partim) was treated exactly as was T.503.

consistent regression of yield on nitrogen occurs within the fourth, fifth, seventh, and eighth nitrogen lines of T. 503, however, and since also the effect of increased potassium dose, within these lines, was small and statistically not significant, the phosphorus effects within T. 508 (partim) will be compared with all of those effects which occur within these four nitrogen lines of T. 503. The part of T. 503 corresponding with these four nitrogen lines will be referred to as "T. 503 (partim)." The phosphorus effects within T. 503 (partim) are shown in table 5.

Whereas the mean yields of the treatments containing phosphorus are about equal in T. 508 (partim) and T. 503 (partim), viz., 49.4 and 50.8 tons respectively, the mean phosphorus effect within the latter experiment is +30.1 tons against only +9.7 tons in the former experiment. After increase of the latter figure by 25 per cent, on account of cycle length, the difference is +18 tons,

TABLE 5

Effects, in tons per hectare, of the single phosphorus dose within T.503 (partim)

TREATMENTS		EFFECTS	YIELDS OF TREATMENTS WITHOUT PHOSPHORUS
NPK	NPK		
412	402	+28.3	12.0
212	202	+19.7	22.3
112	102	+40.3	22.3
012	002	+12.1	25.7
411	401	+36.9	24.9
211	201	+24.0	24.9
111	101	+36.9	24.9
011	001	+42.9	8.6
Mean phosphorus effect.................		+30.14	
Mean yield without phosphorus..........			20.70
Mean yield with phosphorus.............		50.84	

which is statistically significant, since the upper fiducial limit at its 2 per cent level of significance equals +16.5 tons.[13]

The difference in phosphorus effect is due to the differential soil treatment during the sisal prehistory of T. 508 (partim) and T. 503 (partim), i.e., to fertilization with potassium in the former but not in the latter. Thus a quantity of indigenous phosphorus, equivalent to 18 tons of tapioca yield, was less available to tapioca in T. 503 (partim) than in T. 508 (partim), because in the sisal prehistory of the former its soil had not been fertilized with potassium. Evidently, the potassium fertilizer applied at the beginning of T. 503

[13] This statistical comparison is assumed to be valid, because the comparison made is not between yields but between yield differences of one block and those of two other blocks, whereas simultaneously the fertility of the one block is approximately equal to that of the two others, if all are fertilized with phosphorus.

(partim) had been unable, at least to any extent, to take the place of the periodical fertilizations with potassium during the sisal cycle of S. 93.

Thus the previous evidence in connection with the sisal experiment S. 93 is confirmed. It may be restated as follows: The low availability of the indigenous phosphorus in the soil of T. 503 was due to reduction of the original rather high availability, as during the grazing period with its grass cover, by growth of a pure culture of sisal during 6 years and 10 months without fertilization with potassium, whereas the indigenous potassium was only sufficient for about $1\frac{1}{2}$ years of healthy sisal growth.

FURTHER ANALYSIS OF THE FACTORS INFLUENCING AVAILABILITY OF INDIGENOUS PHOSPHORUS

The value of 18 tons of yield, by which the phosphorus-free plots of T. 508 (partim) appeared to surpass the phosphorus-free plots of T. 503 (partim), is smaller by 5.2 tons than the difference between the yield maximum attainable with the indigenous phosphorus in T. 503 (cont.) and that in T. 503 (partim). From this it should not be concluded, of course, that the improvement in the availability of the indigenous phosphorus in the phosphorus-free plots of T. 503 (partim) has raised the availability above that of the soil at the end of the grazing period. The phosphorus reserves were considerably smaller in the soil of T. 508 (partim) than in that of T. 503 (partim), since the sisal in S. 93 had extracted more phosphorus from the former than from the latter, the difference having previously been found to be equivalent to more than 200 tons of tapioca yield. In view of this fact, the difference of 5.2 tons appears reasonable. Anyway, it may safely be said that the increase in availability of the indigenous phosphorus, which occurred within the fourth and seventh nitrogen lines of T. 503 after harvesting, has virtually restored the availability to its status at the end of the grazing period.

The total restoration took place during the two tapioca cycles. It is evident, however, from table 2 that the part that took place during the first cycle was very small in comparison with the part thereafter. This fact is not consistent with the assumption that the potassium fertilizer, as the cause of the restoration, acted in a direct way, since in that case its activity would be expected to be greatest immediately after its application, i.e., at the beginning of T. 503. The same inconsistency with such an assumption was encountered in the case of the corresponding availability restoration with a sisal crop instead of tapioca, as reported elsewhere (2). There it was found that such restoration could be attained by growing sisal in the deteriorated soil with the aid of a liberal, half-yearly fertilization with potassium. In this case the restoration became apparent only about 3 years after the planting of the sisal, and its completion required $2\frac{1}{2}$ more years. Thus the total restoration took $5\frac{1}{2}$ years in the case of sisal, against only $2\frac{3}{4}$ in the case of tapioca, a difference in time which is inconsistent with this assumption.

A second assumption, that the activity either of the tapioca or of the soil

microorganisms was the direct cause of the restoration, is inconsistent with the fact that the restoration took place almost entirely after the first cycle. According to each of these assumptions this restoration should have been, per unit cycle length, at least as effective during the first cycle as during the second.

Consequently, it is suggested that the restoration took place through cooperation of the macrobiotic and the microbiotic processes, potassium fertilization having enabled this cooperation. A feature of the variation between the eight second-cycle yields of the fourth and seventh nitrogen lines is in favor of this suggestion, as will be shown presently.

It has already been mentioned that a strong positive regression of yield on nitrogen occurred within the treatments of said lines after the two without nitrogen were discarded. It is evident from the diagram, however, that the mean yield of the two treatments without nitrogen is considerably higher than that of the four treatments with the two lowest nitrogen doses. The corresponding mean nitrogen effect equals −9.9 tons and is statistically significant (table 2, No. 8). This negative nitrogen effect is consistent with the previously noted, negative regression of yield on nitrogen, occurring within each of the first and third nitrogen lines of the same cycle. It is easily explained by the low concentration of the available indigenous phosphorus reached with the attainment of the corresponding yield maximum, against a simultaneous considerable concentration of the available indigenous nitrogen augmented by the considerable quantities of fertilizer nitrogen applied through the corresponding single and double doses.

The first positive regression of yield on nitrogen, however, would be inconsistent with this simultaneous negative nitrogen effect, had tapioca yield been affected directly in both instances. Consequently, it must be concluded that the aforementioned positive regression of yield on nitrogen is an expression of an indirect influence on yield through nitrogen fertilization.

It is suggested, that, whereas within the fourth and seventh nitrogen lines of the second cycle, the fertilizer nitrogen suppressed tapioca yield through its unfavorable ratio with the available indigenous phosphorus, it could, on the other hand, again raise the suppressed yield through its positive effect on the availability of the indigenous phosphorus by stimulating the activity of the soil microorganisms in a correspondingly favorable way. This suggestion is consistent with the one previously made, that the considered reversion of the deteriorated availability status of the indigenous phosphorus took place through cooperation of the macrobiotic and the microbiotic processes.

On the basis of this suggestion it must be inferred that the cooperation had been made possible by fertilization of the plots of the fourth and seventh nitrogen lines with potassium at the beginning of T. 503. The importance of this fertilizer in the availability reversion is further emphasized by another feature in the variation between the eight second-cycle yields of the fourth and seventh nitrogen lines.

After the variation already explained, the difference in effect between the

double and the single potassium dose, within these lines, may be estimated at the mean of the four differences between the corresponding points of these lines. This mean difference equals +5.8 tons and is statistically significant (table 2, No. 9).[14] It proves that the favorable effect of the suggested cooperation between the macrobiotic and the microbiotic processes on the availability status of the indigenous phosphorus became greater with increased doses of potassium fertilizer, within the limits concerned.

SUGGESTED CONCLUSIONS

The factors found to affect the suggested cooperation between the macrobiotic and the microbiotic processes and their modes of influence in regard to the improvement in the deteriorated availability status of the indigenous phosphorus may be summarized as follows:

This cooperation was made possible by the application of potassium fertilizer.

It was positively affected by increasing the potassium dose from single to double.

It was positively affected by increasing the nitrogen dose from single to quadruple, in the presence of potassium fertilizer.

It did not become apparent until a certain number of years after the fertilization with potassium.

The first evidences were noted 1½ years earlier in the case of tapioca than in that of sisal.

The effect lasted about 3 years longer in the case of sisal than in that of tapioca.

On the basis of these factors, the cooperation is suggested to consist of the utilization by the soil microorganisms of the sun's energy which was stored in the organic material and which was liberated from the crop plants and placed at the disposal of the soil microorganisms.

For such utilization, the soil microorganisms would need potassium fertilizer for their own growth, and should profit from increased doses, at least within certain limits, in a soil very poor in available indigenous potassium; and it is quite natural that they should profit at the same time from simultaneously applied nitrogen fertilizer.

Such utilization, moreover, can begin only after a certain lapse of time, since the liberation of the organic material from the crop plants and its incorporation into the soil cannot be expected to take place to any considerable extent in the earlier phases of crop development. In the case of sisal, such utilization should begin later than in that of tapioca, since in a sisal crop the full-grown leaves are cut and removed from the field, and thus only liberated root material can be disposed of by the soil microorganisms, whereas the leaves of tapioca are not removed from the field, and leaf shedding usually begins about 3 months after planting. Furthermore, the cooperative process would be expected to receive a great stimulus in tapioca culture on account of the organic residues put at the disposal of the soil microorganisms on the occasion of the change-

[14] The yield maximum attainable with the indigenous phosphorus in the second cycle, amounting to 52.7 tons (table 3), may be estimated correspondingly 5.8 tons higher, without changing essentially the inferences made thus far.

over from one to another cycle. These residues comprise almost the entire root system, waste pieces of tubers, and pieces of fresh leaves and stems left in the soil. In sisal culture such a stimulus is absent, since harvesting consists in the periodical removal of some of the leaves from the living plants.

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SYNTHETIC SOIL AS A BACTERIOLOGICAL CULTURE MEDIUM[1]

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A few years ago (2, 3) attention was directed to the fact that a certain soil would deteriorate as a medium for the cultivation of some soil bacteria if allowed to remain air-dry for an appreciable length of time. It was thought that this phenomenon might be related in some way to the state of the colloids in such soil. Because of the complex composition of natural soil, it seemed logical to search for a synthetic soil in which the phenomenon could be studied with fewer complicating factors. This problem was attacked by following the idea previously suggested by Madhok (6), who proposed a mixture of sand and bentonite, with or without humus, as a favorable medium for soil bacteria.

During the course of this investigation, more extensive data have been obtained than are included in the accompanying tables. Much of this material, not even summarized here, suggests that even in the simple mixtures employed in this work, there are factors operating which are not yet understood. For the purpose of this paper, selections have been made from the data, to illustrate the points that can be regarded as sufficiently established.

EXPERIMENTAL

The methods employed varied but were always essentially as follows:

To make the synthetic soil, the sand and colloid (usually bentonite) were mixed dry, together with 1 per cent by weight of $CaCO_3$. The ratio of sand to colloid was varied in a preliminary experiment (table 1); but after what seemed to give approximately optimum conditions was determined, the ratio of 0.5 gm. colloid to 9.5 gm. sand was uniformly maintained. Two kinds of sand were studied: first, sea sand from the beach at La Jolla washed in distilled water until free from chloride and ignited to free it from organic matter; second, a quartz sand purchased from the Ottawa Silica Co., of Ottawa, Illinois, and designated as "Crystal Silica."[3] Ordinarily, in each experiment, a con-

[3] According to the mechanical analysis of the product furnished by the manufacturer, 60 per cent of its particles fall between 0.42 and 0.15 mm. in diameter.

trol tube without any colloid was included; in this the $CaCO_3$ and nutrients were mixed with the sand alone.

When the ingredients were mixed dry, 1 per cent by weight of glucose was included to furnish energy and carbon for the bacteria. These dry ingredients were placed in test tubes of 18–20 mm. outside diameter, 10 gm. to a tube. It was considered safe, when necessary, to allow this mixture to stand a day or more before sterilization.

Later a nutrient solution containing the compounds called for in any particular experiment was added. This solution was of such strength that 0.3 cc. would be required for each tube; thus, the amount of fluid plus the volume of the inoculum subsequently added totalled 1.3 cc. Previous investigations had shown that for 10 gm. of sand alone this amount of water furnished approximately optimum moisture content—about half the water-holding capacity of the sand. When the mixture also contained a colloid, additional distilled water was needed to assure optimum conditions; thus to quartz sand with 5 per cent bentonite, 0.5 cc. additional water was added to bring the total amount of fluid (including inoculum) in the tube up to 1.8 cc. Immediately after addition of the nutrient solution, the tubes were sterilized at 15 pounds' steam pressure, ordinarily for 1 hour.[4]

The nutrients thus added contained ordinarily, in addition to the glucose, mineral salts containing the ions, K^+, NH_4^+, $PO_4^=$, and $SO_4^=$; but they were varied in certain experiments where the value of the colloid as a source of some of these ions was being investigated. Ordinarily the nutrients did not include magnesium or any of the trace elements (except sulfur). These were omitted because they had not been found necessary in synthetic laboratory media for the organisms under investigation. It was assumed that if the trace elements were present in such media in sufficient abundance, they would also occur in the sand used in this work. This assumption may have been incorrect, as explained subsequently. In each experiment certain basal nutrients, shown in each table, were employed. To these, the ingredients under investigation were added, as indicated in the tables.

After cooling, the tubes were inoculated with one of the test organisms. The inoculation was performed by adding 1 cc. of a suspension of the organism, washed off a 24-hour agar-slant culture with sterile distilled water. After inoculation the tubes were incubated 7 days at 30°C., and counts were then made.

The test organisms

The organism used in almost all the tests was a culture of *Bacterium radiobacter* (Beijerinck) Löhnis.[5] In many of the experiments, results with this

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[4] It is not overlooked that heating at such a temperature for 1 hour may change the nature of the ingredients in the mixture. This point is discussed subsequently.

[5] Furnished by Dr. Hofer, of the writers' laboratory, as representing a typical strain of this organism.

species were compared with those obtained with *Bacterium globiforme* Conn. The reason for employing the former the more regularly was that it was found to give the most striking differences and the most consistent results of any species investigated.   In one experiment tests with several other soil bacteria were made.

Method of counting

The counts at the end of the 7-day incubation period were ordinarily made by means of the microscope, on smears stained with 1 per cent rose bengal in 5 per cent phenol.   Comparisons were occasionally made with the plate method of counting, using a yeast-extract-mannitol agar and incubating the plates at 30°C. for 7 days.   When both methods were used, the two sets of counts were never far apart, but the plate method showed much greater irregularities than the microscopic procedure.   In fact, the inconsistencies proved so great with the plate method that this was eventually omitted, and the remaining results

TABLE 1
Preliminary bacterial counts to indicate optimum ratio of sand and bentonite
Counts in millions per gram after 7 days' incubation

COMPOSITION OF SOLID SUBSTRATUM*	BACT. RADIOBACTER	BACT. GLOBIFORME
Sea sand + 1 per cent bentonite............................	2,748	1,818
Sea sand + 2.5 per cent bentonite..........................	4,123	5,370
Sea sand + 5 per cent bentonite...........................	3,987	7,935
Sea sand + 7.5 per cent bentonite..........................	3,968	4,260
Sea sand + 10 per cent bentonite...........................	5,430	8,363

* Basal nutrients per 10 gm. substratum: 0.1 gm. glucose, 0.1 gm. $CaCO_3$, 0.03 gm. K_2SO_4, 0.03 gm. $(NH_4)_2HPO_4$.

were obtained wholly by the use of the microscope.   No plate counts are included among the data in this paper.

OPTIMUM MIXTURES OF SAND AND COLLOID

Madhok employed 2.5 per cent bentonite in his synthetic soil; but it seemed well to investigate other proportions of sand to colloid.   Accordingly, a preliminary experiment was set up in which the amount of bentonite was varied from 1 to 10 per cent of the total weight.   The results are given in table 1. Although the highest counts were obtained with 10 per cent bentonite, those with 7.5 per cent were lower than those with 5 per cent; and it was concluded that little advantage was gained by using more than the last mentioned percentage.   Throughout the rest of the work, therefore, 5:95 was the standard ratio employed of colloid to sand.

It is of interest to compare these counts in synthetic soil with those ordinarily obtained in natural soil.   When these same organisms are inoculated into various samples of normal field

soil, with the same nutrients added, the counts obtained by the same technic varied from about 2 to about 5 billion per gram. The lower counts were observed for soils that had been stored for some time in air-dry condition: counts of about 4 billion per gram were considered normal for freshly gathered soil. It will be seen that those obtained in the synthetic soil containing sea sand and 2.5–10 per cent bentonite were ordinarily higher than this.

TABLE 2

*Growth of Bacterium radiobacter and Bact. globiforme on sand with and without bentonite**

Counts in millions per gram after 7 days' incubation

BACTERIUM RADIOBACTER		BACTERIUM GLOBIFORME	
Sand without colloid	Sand + 5 per cent bentonite	Sand without colloid	Sand + 5 per cent bentonite
Sea sand			
855	3,987	809	7,935
563	5,220	2,588	5,808
2,380	3,280	2,235	5,355
2,398	5,835	2,845	4,538
778	5,345	865	7,590
2,415	5,325	1,075	4,375
3,088	5,106	2,864	5,436
1,570	5,870	2,996	6,166
2,358	6,828	1,666	5,976
1,328	5,236	1,012	5,088
1,954	4,328	730	4,580
3,176	7,124	1,976	5,032
3,370	7,028	4,450	6,216
Quartz sand			
2,154	5,506	2,076	3,250
2,456	6,120	1,174	4,752
1,422	4,654	1,467	1,910
2,854	7,484	2,596	6,063
3,436	6,636	1,083	7,090
1,296	6,680	1,382	868
2,228	3,636	1,176	1,090
2,314	5,860	1,600	1,314
2,232	5,736	1,094	2,712
2,290	5,108	1,706	1,718
2,812	4,812	1,666	1,830

* Basal nutrients per 10 gm. substratum: 0.1 gm. glucose, 0.1 gm. $CaCO_3$, 0.03 gm. K_2SO_4, 0.03 gm. $(NH_4)_2HPO_4$.

COMPARISON OF SEA SAND AND GROUND QUARTZ

As a test of the significance of variation in the sand, counts were made during 2 years of the bacterial numbers, in media using sea sand and quartz sand, each with and without the colloid. The data are given in table 2.

Three points stand out clearly from this table: first, the count obtained in the presence of bentonite was ordinarily at least twice that with sand alone;

second, with *Bacterium radiobacter* this stimulation was observed in every instance; third, with *Bacterium globiforme* in some instances the count was at least as low with the bentonite as without it, *but all these instances occurred with quartz sand.* The exact significance of this last observation has not yet been learned, but it is evident that for the latter organism the sea sand employed was a better constituent of synthetic soil than was the quartz sand.

This variability of *Bacterium globiforme* in the quartz sand is especially noticeable in the series containing bentonite and seems to indicate the presence of some variable factor which is influencing the results. No satisfactory explanation of this uncontrolled factor was obtained in the course of the work, although possibly it may be associated with the effect of sterilization on the ingredients of the mixture. Because of this variability, whenever quartz sand

TABLE 3

Growth of Bacterium radiobacter as influenced by various periods of sterilization of substratum*

Counts in millions per gram after 7 days' incubation

TIME OF STERILIZA-TION	SAND WITHOUT COLLOID				SAND + 5 PER CENT BENTONITE			
hours	1st test	2nd test	3rd test	4th test	1st test	2nd test	3rd test	4th test
Quartz sand								
1	.....	2,290	3,892	2,608	.....	5,108	6,088	5,768
2	1,250	2,862	2,717	1,948	2,392	5,620	1,796	3,336
3	1,674	.....	1,606	1,786	1,088	.....	1,309	3,418
Sea sand								
1	.....	1,954	3,210	3,488	.....	4,328	5,748	6,048
2	.....	2,480	3,446	2,950	.....	2,650	5,252	5,480
3	.....	.....	2,142	2,364	.....	.....	5,036	5,428

* Basal nutrients per 10 gm. substratum: 0.1 gm. glucose, 0.1 gm. $CaCO_3$, 0.03 gm. K_2SO_4, 0.03 gm. $(NH_4)_2HPO_4$.

was employed in any of the experiments, the counts obtained in the control tubes rarely seemed to have any significance. For this reason experiments carried on with this organism in quartz sand are not ordinarily included in the tables.

EFFECT OF VARYING PERIODS OF STERILIZATION

A similar difference between the two kinds of sand was brought out by *Bacterium radiobacter* when periods of sterilization at 15 pounds' steam pressure were longer than 1 hour. The results are given in table 3.

It is clear from this table that the counts were usually lower when the synthetic soils were sterilized longer than 1 hour, and that the lowest counts were observed after 3 hours' heating, the longest period employed. This effect was

most pronounced in the mixture of bentonite and quartz sand, and least in the mixture of bentonite and sea sand. With sand alone the decrease was evident but not so great as with the quartz sand and bentonite. As a result, the counts obtained after 3 hours' sterilization were scarcely higher with quartz sand and bentonite than with quartz sand alone. As these results were obtained with *Bacterium radiobacter*, it is apparent that under such conditions sea sand can be a better substratum than quartz sand for this organism also.

The explanation of this phenomenon is uncertain. Apparently the bentonite is changed in some way by the prolonged heating. This was evident, before the counts were made, by the color of the suspension obtained when the various mixtures of quartz sand and bentonite were mixed with water. No such difference in color of the suspensions was noticed when the mixture contained sea sand instead of quartz sand. It was also observed throughout the work that the bentonite was more easily incorporated with the sea sand than with the ground quartz, and presumably in some way the former protected it from the effects of prolonged heating. What change occurs on heating is a matter of speculation. The sorptive properties might well be lessened, but no conclusive evidence to that effect has yet been obtained.

Undoubtedly, sterilization for even 1 hour must produce some harmful effect. This may well account for the frequent lower counts obtained with *Bacterium globiforme* in the quartz sand mixtures. Unfortunately, however, shorter periods of heating at the temperature employed do not seem to effect complete sterilization.

INFLUENCE OF VARIOUS TYPES OF COLLOIDS

A series of experiments was designed to show whether other types of colloids have the same stimulating effect as does bentonite on the numbers attained by the two test organisms. The results, given in table 4, show that every one of the colloids caused a marked increase in the numbers reached by *Bacterium radiobacter*. This is very interesting, because the various types of colloids employed differ considerably in their chemical and physical characteristics. All but the bentonite had been extracted from soil and represented the several types of colloids indicated in the first column of the table. Approximately the same amount of stimulation occurred with each of the types. In general, this organism attained greater numbers with the soil colloids than with the commercial sample of bentonite.

For the other test organism, *Bacterium globiforme*, only one series of figures is given. Another test was made with this organism, but it was in quartz sand, and as has been explained, under such conditions results are unreliable. The one test reported gives essentially the same indications as those obtained with the other organism, except that with one soil colloid (the Redding colloid of kaolinitic type) no increase in the count was observed.

Special interest attaches to the figures given in the last row of this table— results with the colloid from a Volusia soil in New York State. The soil in

question is of rather low productivity and proves also to be a poor medium for the growth of either of the test organisms, especially after it has been stored some time in air-dry condition (3). Apparently, however, the colloidal material which can be leached out of this soil can be just as beneficial, under the conditions of this experiment, as the others studied. Of particular interest are the following observations: first, when this colloid was mixed again in essentially the original ratio with the coarser fractions from the mechanical analysis of this soil, the reconstituted soil thus formed proved a better medium for the test organisms than did the original soil; second, when a sample of this soil had been left in air-dry condition long enough to become a poor medium for

TABLE 4

Bacterial numbers as influenced by various types of colloids

Counts in millions per gram after 7 days' incubation

COLLOID ADDED (IN 5 PER CENT QUANTITIES) TO SAND*			BACTERIUM RADIOBACTER				BACTERIUM GLOBIFORMI (SEA SAND)
	Source		1st test (sea sand)	2nd test (quartz sand)	3rd test (quartz sand)	4th test (quartz sand)	
Type	Soil Series	Location					
None.................	....	....	2,397	1,250	1,296	2,314	2,845
Bentonite............	....	....	5,835	2,392	6,680	5,860	4,538
Beidelitic............	Yolo	California	5,490	.....	6,808	.....	3,335
Kaolinitic............	Aiken	California	7,925	.....	5,822	.....	7,225
Kaolinitic............	Redding	California	7,700	.....	6,316	.....	2,013
Illitic................	Hanford	California	6,640	.....	9,672	.....	4,380
Kaolinitic............	Cecil	North Carolina	.....	8,232	7,904	7,796	.....
Bentonitic............	Palouse	Washington	.....	7,528	7,796	7,408	.....
Unidentified mixtures	Hagerstown	Pennsylvania	.....	8,722	7,916	8,232	.....
of kaolinitic and	Muskingum	Ohio	.....	8,052	8,188	8,888	.....
beidelitic..........	Volusia	New York	.....	8,860	7,924	8,356	.....

* Basal nutrients per 10 gm. substratum: 0.1 gm. glucose, 0.1 gm. $CaCO_3$, 0.03 gm. K_2SO_4, 0.03 gm. $(NH_4)_2HPO_4$.

the growth of these organisms, its beneficial properties for this purpose were restored by adding 5 per cent of its own colloidal material that had been leached out of another sample of the same soil. These observations are entirely unexplainable at present but do suggest that there is a complicated relationship between bacteria and these soil colloids.

Primary nutrient elements possibly supplied by colloids

The question as to why colloids are valuable in bacterial nutrition has been frequently investigated during recent years. Thus Albrecht and McCalla (1) have been developing special media which contain colloids saturated with the bases needed in nutrition and claim that in this way the latter are furnished

in a more favorable form than if they were present as inorganic salts. Especially interesting is their observation (5) that the legume organism becomes abnormal if grown on such a medium saturated with barium but returns to its normal condition if furnished with a calcium-saturated colloid. This observation seems to furnish some explanation of the earlier findings of Killinger and Smith (4) that legume bacteria and *Azotobacter* cultures seem to secure energy and possibly nutrients from soil colloids. Sokoloff (7), on the other hand, reports that the production of nitrate and total nitrogen from soil is stimulated by sodium-saturation of the soil colloids and depressed by calcium-saturation. Although it is difficult to coordinate all such findings, there appears to be no question but that colloids may act as carriers of calcium or nutrient ions. Accordingly, it seemed not improbable that they might serve such a function in a synthetic soil.

Attention was first given to the question whether the colloid in the present investigation might be supplying one of the primary nutrient elements, nitrogen, potassium, or phosphorus. It seemed out of the question that it could be needed as a calcium carrier, because the $CaCO_3$ added (primarily to neutralize acids produced) should furnish all the calcium required. The three primary nutrient elements, on the other hand, were supplied in smaller quantity, as the salts used were soluble, and an excess of nearly any soluble salt proved detrimental. It was possible, therefore that the colloid might supply a deficiency in one of these elements without allowing the accumulation of any harmful ion after removal of the needed nutrient element by the bacteria. It seemed entirely possible that either K ions or nitrogen as NH_4 ions might be furnished by the colloid in a form available to the bacteria. That phosphorus could be furnished similarly seemed less likely on theoretical grounds, but the possibility appeared worth investigating. The investigation was carried out in two ways: first, by changes in the nutrient salts added, so as to furnish the important ions in varying quantities; second, by treating the bentonite in such a way as to remove the base or bases with which it was originally saturated and to replace them with others.

It was readily shown that natural bentonite could not act as a source of nitrogen. When the ammonium phosphate was replaced with potassium phosphate, so few bacteria were visible under the microscope, even with bentonite present, that accurate counts were out of the question. The fact that the bacteria were all but lacking is good evidence that nitrogen is not supplied by the colloid. Further evidence to this same effect was obtained with the NH_4-saturated bentonite. (See table 5.)

In replacing the base or bases present in the natural bentonite, the following procedure was employed:[6] The bentonite was treated with dilute acetic acid to replace the original bases with H^+, and the excess fluid was drawn off through a

Berkefeld filter. The H-bentonite thus obtained was divided into six portions, one to be used without further treatment, the others for replacement of the H ions with K^+, NH_4^+, Ca^{++}, Mg^{++}, and Ba^{++}. This was done by washing each through a filter of the same type with a $0.001N$ solution of the acetate of the proper base. Then each portion was washed about five times, through the filter, with methyl alcohol.

Table 5 gives the results obtained when the synthetic soil was prepared with each of these treated bentonites as well as with the natural product. (The natural bentonite was assumed to be saturated with potassium or with potassium and sodium, but no tests to determine this point were made.) From the results with *Bacterium radiobacter*, it will be seen that some stimulation has occurred with every sample, but distinctly less with the NH_4-bentonite and the Ca-bentonite than with the others. In the case of *Bacterium globiforme*,

TABLE 5

Bacterial counts as affected by varying the cation with which bentonite is saturated

Counts in millions per gram after 7 days' incubation

COMPOSITION OF SOLID SUBSTRATUM*	BACTERIUM RADIOBACTER		BACTERIUM GLOBIFORME	
	1st test	2nd test	1st test	2nd test
Sea sand without colloid.....................	778	1,570	865	2,996
Sea sand + 5 per cent natural bentonite........	5,340	5,870	7,590	6,166
Sea sand + 5 per cent H-bentonite............	4,800	8,352	6,105	5,740
Sea sand + 5 per cent K-bentonite............	4,905	5,604	7,795	3,034
Sea sand + 5 per cent NH₄-bentonite..........	3,445	3,826	1,545	2,822
Sea sand + 5 per cent Ca-bentonite...........	2,835	4,888	1,685	4,271
Sea sand + 5 per cent Mg-bentonite...........	6,320	4,470	7,710	3,880
Sea sand + 5 per cent Ba-bentonite...........	6,060	4,346	3,885	4,676

* Basal nutrients per 10 gm. substratum: 0.1 gm. glucose, 0.1 gm. $CaCO_3$, 0.03 gm. K_2SO_4 0.03 gm. $(NH_4)_2HPO_4$.

these two colloid samples gave low counts, but less consistency was noted in the findings. This is another illustration of the unreliability of the results with this organism. In general, the findings seem to show that the bentonite has some advantage to the bacteria other than furnishing them with one of the replaceable bases under investigation in this experiment. The high counts obtained with the Ba-bentonite are especially striking, as it was thought in advance that this might have a toxic effect. The low counts obtained with the NH_4-bentonite furnish additional evidence that the advantageous effects of the natural colloid are not due to its ability to supply nitrogen.

Results are given in table 6 of the experiment in which changes were made in the nutrient salts added, so as to investigate the effect of omitting phosphorus and of varying the amount of potassium furnished. (In this experiment results of one test with *Bacterium globiforme* in quartz sand are included because the results were consistent and the series obtained in sea sand was incomplete.)

The results in the first column were obtained with no phosphorus but with added nitrogen and potassium. The other columns give the results with nitrogen and phosphorus present, but with varying quantities of K_2SO_4. Omission of the phosphorus proved distinctly detrimental. It is clear that its lack was not appreciably overcome by the presence of the bentonite. This colloid can hardly be regarded, therefore, as a satisfactory source of phosphorus.

TABLE 6

Bacterial counts as influenced by bentonite with and without potassium or phosphorus in the nutrients present

Counts in millions per gram after 7 days' incubation

COMPOSITION OF SOLID SUBSTRATUM*	NO P [0.03 GM. K₂SO₄ + 0.04 GM. (NH₄)₂SO₄]	0.03 GM. (NH₄)₂HPO₄				
		No K [0.04 gm. (NH₄)₂SO₄]	0.012 gm. K [0.03 gm. K₂SO₄]	0.0235 gm. K [0.06 gm. K₂SO₄]	0.039 gm. K [0.1 gm. K₂SO₄]	0.051 gm. K [0.13 gm. K₂SO₄]
Bacterium radiobacter						
1st test (sea sand):						
No colloid......................	970	1,271	2,398	2,475	.....	.....
5 per cent natural bentonite......	1,625	6,854	4,303	5,940	.....	.....
5 per cent Mg-bentonite..........	1,970	3,075	5,580	.....	.....	.....
2nd test (quartz sand):						
No colloid......................	1,552	1,948	3,145	3,486	1,172	759
5 per cent natural bentonite......	1,360	4,737	7,060	7,448	3,428	4,016
Bacterium globiforme						
1st test (sea sand):						
No colloid......................	568	624	1,655	1,240	.....	.....
5 per cent natural bentonite......	1,350	5,378	4,855	4,890	.....	.....
5 per cent Mg-bentonite..........	965	2,095	5,425	.....	.....	.....
2nd test (quartz sand):						
No colloid......................	1,312	1,770	1,840	1,064	920	744
5 per cent natural bentonite......	2,056	4,990	6,579	5,772	5,512	4,878

* Basal nutrients per 10 gm. substratum: 0.1 gm. glucose, 0.1 gm. $CaCO_3$.

Omission of the potassium, however, had a somewhat different effect. With the sand alone or with the sand plus Mg-bentonite, its omission decreased the numbers of bacteria, but when the natural bentonite was present no decreases were observed from omitting this element. This suggests that the natural bentonite can supply potassium. · It is also clear that there was some other factor involved than the potassium furnished by the colloid, as the counts

without colloid were always much lower than those in the mixtures with bentonite, even when potassium was present.

In connection with this experiment it should be remarked that the quantities of the various salts ordinarily employed were determined in a somewhat arbitrary manner, although previous work in natural soils had shown them to be not far from the optimum. As it seemed entirely possible that the quantity normally added (only 0.0117 gm. K per tube) was insufficient in a synthetic soil, the question was given consideration. The data obtained are given in the last four columns of the table. In these tests, varying quantities of K_2SO_4 (up to 0.051 gm. K) were investigated. It will be seen that doubling the normal quantity had no effect on the counts but that the addition of larger amounts proved detrimental. Whether the detrimental effect was due to excess of the K or SO_4 ions was uncertain.

In summarizing these results it may be said that either organism can clearly obtain its needed potassium (but not phosphorus) from the bentonite, yet the increase due to the colloid was distinctly greater than when the K ions were added in the form of K_2SO_4. This indicates that the colloid has some other beneficial property.

Other beneficial factors possibly furnished by the colloid

It is evident from the foregoing results that the colloid has some other function in a synthetic soil, and presumably in a natural soil as well, than acting as a carrier of potassium. This does not seem to be serving as a carrier of calcium or nitrogen, in the case of the particular synthetic mixtures and the test organisms used in this work. Various theories have been considered, of which the most probable seem to be the following: (a) The colloid may serve as point of attachment for the bacteria, the additional surface thus presented furnishing the organisms better physical conditions for growth; (b) it may absorb or adsorb the harmful by-products of bacterial growth; (c) it may furnish the necessary "trace elements," which are required in such small quantities that the base-exchange treatment given to some of the colloids allowed them to remain in sufficient abundance to meet the nutrition requirements; (d) it may supply some needed organic growth factor, perhaps some "vitamin."

These four factors are difficult to investigate singly. In regard to the first, it is to be noted that the organisms were usually observed most abundantly in the masses of colloidal material, which suggests that they may use this material for attachment, but on the other hand, almost any of the theories might explain the occurrence of large masses of bacteria in close association with the colloid. The method chosen to eliminate some of these factors was to replace the bentonite with various grades of finely divided carbon. In this way it was possible to provide high adsorptive properties without furnishing as much surface as does a colloid, and since such carbon is usually manufactured by a process of ignition, the possibility of an organic growth factor seemed to be thus eliminated. It was felt that if as good growth could be obtained with

such a carbon as with a colloid, the first and last of the theories could be eliminated, and one would have to accept either the second or the third, or both. Results of this investigation are given in table 7.

It will be seen from this table that the results with the various carbons were very inconsistent, but in many cases as high counts were obtained with a carbon as with bentonite. This seems to indicate that a finely divided carbon *can* supply the bacteria with what they need as well as does a colloid, but that some factor exists, other than the adsorptive properties of the carbon, which is sometimes present and sometimes absent. This strongly suggests the possibility that needed trace elements are sometimes present in the carbon or, if they are lacking, that they may sometimes be supplied inadvertently as impurities of some other ingredient used.

TABLE 7

Growth of Bacterium radiobacter on mixtures containing either bentonite or finely divided carbon

Counts in millions per gram after 7 days' incubation

COLLOID OR CARBON MIXED WITH QUARTZ SAND*	1ST TEST	2ND TEST	3RD TEST	4TH TEST	5TH TEST	6TH TEST
None	2,812	2,680	2,628	2,294	2,570	3,026
1 per cent Kahlbaum carbon	4,744	4,824	2,704	4,732	4,536	5,640
1 per cent Darco carbon S51	1,962	2,194	5,300	2,862	5,272	5,488
1 per cent Darco carbon D-3	.....	.....	4,172	2,002	2,560	1,992
1 per cent Darco carbon G-60	.....	.....	4,264	4,036	3,996	5,024
1 per cent animal charcoal	5,288	4,700	.....	.....	.....	.....
1 per cent lampblack	4,442	6,088	.....	.....	.....	.....
5 per cent bentonite	4,812	5,700	5,284	7,228	3,508	8,170

* Basal nutrients per 10 gm. substratum: 0.1 gm. glucose, 0.1 gm. $CaCO_3$, 0.03 gm. K_2SO_4, 0.03 gm. $(NH_4)_2HPO_4$.

To investigate the question further a nutrient solution was made up containing traces of the following salts: $FeSO_4$, $ZnSO_4$, $Al_2K_2(SO_4)_4$, KI, $KMnO_4$, Na_2SiO_3, $CuSO_4$, $NiCl_2$, $LiCl$, $MgSO_4$. Table 8 shows the results obtained when all of these salts or certain combinations of them were added in traces to quartz sand with the usual basal nutrients but no colloid. Consistently high counts were again obtained in the presence of bentonite, but results were inconsistent when this colloid was omitted and the trace elements were added. So far as these results are regular enough to be significant, they indicate magnesium to be the most important of the trace elements. Two of the counts made without colloid but with a trace of $MgSO_4$ were as high or almost as high as those with bentonite, whereas the other two were as low as with sand alone. The two counts obtained with all the trace elements except magnesium, but no colloid, were also high, but this combination was not tested often enough to learn whether results with it would be consistent.

The fact that high counts could be obtained without colloid when either $MgSO_4$ or carbon was added, but that such results were inconsistent, suggested

that both factors might be involved, that is, the colloid might absorb harmful by-products and might furnish the traces of magnesium needed but not sup-

TABLE 8

Growth of Bacterium radiobacter as affected by addition of trace elements to basal nutrients*

Counts in millions per gram after 7 days' incubation

TRACE ELEMENTS ADDED	1ST TEST	2ND TEST	3RD TEST	4TH TEST	5TH TEST	6TH TEST
Quartz sand plus 5 per cent bentonite						
None..........................	5,399	6,802	6,080	7,064	5,296	6,572
All but Mg†....................	6,012	6,664	.....	.....	.....	.....
Quartz sand without colloid						
None..........................	2,812	2,154	2,726	2,874	3,662	2,058
All but Mg†....................	4,708	4,552	.....	.....	.....	.....
Complete†.....................	.....	.....	.....	.....	4,644	2,580
Mg, Fe, I, Mn.................	.....	.....	4,380	3,674	5,152	5,000
Mg, Fe, I.....................	.....	.....	3,856	2,896	.....	.....
Mg, Fe........................	.....	.....	4,372	3,328	.....	.....
Mg............................	.....	.....	4,820	2,844	6,030	2,876

* Basal nutrients per 10 gm. substratum: 0.1 gm. glucose, 0.1 gm. $CaCO_3$, 0.03 gm. K_2SO_4, 0.03 gm. $(NH_4)_2HPO_4$.

† The complete trace elements used in this experiment consisted of $FeSO_4$, $ZnSO_4$, Al_2K_2-$(SO_4)_4$, KI, $KMnO_4$, Na_2SiO_3, $CuSO_4$, $NiCl_2$, $LiCl$, $MgSO_4$.

TABLE 9

Growth of Bacterium radiobacter as affected by addition of finely divided carbon and trace of magnesium to substratum*

Counts in millions per gram after 7 days' incubation

TEST NUMBER	QUARTZ SAND	QUARTZ SAND + 5 PER CENT BENTONITE	QUARTZ SAND + TRACE MgSO₄	QUARTZ SAND + TRACE MgSO₄ + CARBON
1	2,934	6,608	5,540	6,288
2	4,084	7,736	6,674	6,336
3	2,872	6,368	6,476	5,640
4	3,152	5,416	5,632	7,538
5	3,106	5,536	5,628	7,032
6	2,430	5,592	5,512	5,564
7	2,804	6,376	5,108	4,628
8	1,568	6,160	2,800	6,872
9	3,760	5,824	1,876	6,484

* Basal nutrients per 10 gm. substratum: 0.1 gm. glucose, 0.1 gm. $CaCO_3$, 0.03 gm. K_2SO_4, 0.03 gm. $(NH_4)_2HPO_4$.

plied by the regular basal nutrients. The results obtained can be explained on this theory with two additional assumptions; first, that magnesium in sufficient quantity may frequently, but not consistently, be added as an impurity

of some other ingredient; second, that the harmful by-products which the colloid or carbon serves to remove are not always formed in sufficient abundance to be detrimental to growth. If these assumptions are correct, consistently high counts ought to be obtained without colloid if a finely divided carbon and traces of MgSO₄ are added.

In order to test this point four series of experiments were run using sand without colloid or either of the ingredients under investigation, sand plus 5 per cent bentonite, sand plus a trace of MgSO₄, and sand plus 1 per cent finely divided carbon plus a trace of MgSO₄. Nine separate tests were made, the results of which are shown in table 9. In seven of the tests the counts with MgSO₄ alone were as high or nearly as high as with bentonite, but in the other

TABLE 10

*Growth of various soil bacteria in synthetic soil**

Counts in millions per gram after 7 days' incubation

ORGANISM	SAND WITHOUT COLLOID		SAND + 5 PER CENT BENTONITE	
	Sea sand	Quartz sand	Sea sand	Quartz sand
Bacterium radiobacter.............................	1,328	2,232	5,236	5,745
Bacterium globiforme.............................	730	1,094	4,580	2,712
Unidentified nonspore-formers†................	1,304	1,454	3,670	2,254
	1,260	780	2,772	1,612
Mycobacterium coeliacum‡.......................	1,642	1,894	2,360	2,608
Corynebacterium simplex‡........................	1,886	1,438	6,320	2,520
Pseudomonus fluorescens§.......................	1,304	792	3,456	3,106
Bacillus cereus§................................	302	484	910	1,124

* Basal nutrients per 10 gm. substratum: 0.1 gm. glucose, 0.1 gm. CaCO₃, 0.03 gm. K₂SO₄, 0.03 gm. (NH₄)₂HPO₄.

† Of the punctiform-colony type, isolated from local soil.

‡ Named by H. L. Jensen, of New South Wales, and supplied by him.

§ Isolated from local soil and identified by one of the writers.

two they were practically as low as without MgSO₄. When the carbon was added, however, all the counts were nearly the same as with bentonite: in four instances higher, in four lower, and in the ninth almost identically the same.

Although to be conclusive these results should be based on more extensive data, they do indicate the correctness of the foregoing theory and assumptions. It may be concluded that the colloid, in addition to serving as a source of potassium, furnishes the trace of magnesium which the test organism needs, and also acts as an absorbent of harmful by-products that may be present on occasion.

BEHAVIOR OF OTHER SOIL BACTERIA IN THE SYNTHETIC SOIL

The foregoing results were compared with those obtained with a few other kinds of soil bacteria. The results of a series of tests on six kinds of organisms other than the two used in the rest of the work are given in table 10. It is

evident that with every organism higher counts were obtained in the presence of bentonite than in its absence, but in only one instance (*Corynebacterium simplex*) was the count as high as those ordinarily obtained with *Bacterium radiobacter* under the same conditions. It is also noticeable that in most instances a higher count was obtained in the sea-sand mixture than in the quartz-sand mixture. The one spore-former used gave strikingly lower counts, but the beneficial effect of the colloid was noticeable, nevertheless. With this organism the quartz sand gave a higher count than the sea sand.

These observations indicate that the bentonite improves the sand as a medium for any of these organisms, but they suggest that the problem may be different with each species and that it may be difficult to find a synthetic soil equally advantageous for all kinds of soil bacteria.

CONCLUSIONS

A synthetic soil can be prepared by mixing a sand with 2.5–10 per cent of a colloid, plus glucose and $(NH_4)_2HPO_4$ with $CaCO_3$ added in sufficient excess to neutralize any acids produced. In such a mixture the two test organisms (*Bacterium radiobacter* and *Bacterium globiforme*) can attain numbers as high as in the best natural soils investigated. The mixture is also apparently suitable for the growth of other soil bacteria, although this point has not yet been thoroughly investigated.

Although bentonite was employed in most of the work, various other colloids can be used with equally good results.

These synthetic soils can be sterilized for 1 hour at 15 pounds' steam pressure without appreciable deterioration as media for the test organisms, but longer periods of heating have an adverse effect.

The colloid in this mixture serves at least two important functions: first, as a carrier for bases needed by the bacteria, notably potassium and magnesium (undoubtedly calcium also, although this did not affect results in the present work, as $CaCO_3$ was always added in excess); second, as a sorbent of harmful by-products. No evidence is obtained that the additional surface furnished by the colloid is an important factor, *per se*, or that the colloid supplies needed organic growth factors.

The bacteria are not entirely indifferent to the kind of sand employed in the mixture. The washed sea sand used in this work proved better than a ground quartz. The reason for this difference is not yet evident, but it is apparent that the sea sand in some way tends to prevent the harmful effect of sterilization on bentonite.

A good formula for such a synthetic soil is as follows:

Sand (preferably not ground quartz, but the best type is still to be determined)...*gm.* 95
Bentonite or soil colloid..*gm.* 5
$CaCO_3$...*gm.* 1
Glucose...*gm.* 1
$(NH_4)_2HPO_4$..*gm.* 0.3
Water (including that added in inoculum)............................*cc.* 18

In this formula, 1 gm. of a finely divided carbon, such as that used for decolorizing purposes, can be substituted for the 5 gm. of colloid, provided 0.3 gm. K_2SO_4 and a trace (e.g. 0.002–0.003 gm.) of $MgSO_4$ are included. In the latter formula the total water added should be only 16 cc.

These investigations seem to be of value in two different ways: first, they give indication of what factors in the composition of natural soil are most important for the growth of bacteria; second, they suggest the composition of a culture medium for soil bacteria which may have properties similar to natural soil without being of such indefinite composition.

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LABORATORY, GREENHOUSE, AND FIELD METHODS OF STUDYING FERTILIZER NEEDS OF ORCHARD SOILS[1]

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The use of chemical methods for indicating fertilizer needs of soils has received much attention in recent years. Such methods have not replaced greenhouse and field trials, however, particularly where reliability rather than quick result is desired.

The problem of orchard fertilization is complicated by the necessity of dealing with a large, slow-growing, unwieldly, and relatively unresponsive plant. Many years are necessary to carry out satisfactory field studies with trees. Rapid methods may be useful particularly in the fertilization of the cover crop, which when used for green manuring over a period of years becomes of extreme importance to tree nutrition. This paper reports some of the information obtained by using chemical, greenhouse, and field methods principally on soils supporting orchard cover crops.

METHODS

Some of the methods used in the study of the physical and chemical properties of the soil have already been reported (6).

For the greenhouse work, soils were sampled at the depths indicated, sieved to remove stones and trash, and weighed into No. 1 tall, charcoal plate fruit cans, lacquered inside. These cans conveniently hold 400 gm. of soil. Plants were seeded in the cans, and the desired treatments were applied in solution. Insoluble materials such as lime and compost were applied before seeding and were carefully mixed with the soil. Lime was added as calcium carbonate at the rate of 2 tons an acre. Compost was well-rotted barnyard manure and was added at the rate of 50 gm. per 400 gm. of soil.

As a source of potassium and phosphorus, when both were used, five molecular weights of KH_2PO_4 and two molecular weights of K_2HPO_4 were separately dissolved in water and then mixed to make 7 liters of stock solution. The solution was diluted for use to supply 350 p.p.m. of potassium and 217 p.p.m.

of phosphorus.   A molecular solution of $MgSO_4$ diluted to supply 224 p.p.m.
of sulfur and 168 p.p.m. of magnesium was used as a source of sulfur and
magnesium when both were needed.   Nitrogen was supplied as $Ca(NO_3)_2$
made up to contain 200 p.p.m. of nitrogen.[3]   Sulfur alone was supplied as
calcium sulfate, and potassium alone, as the chloride.   Phosphorus alone was
supplied as $CaH_4(PO_4)_2$.   Boron was supplied as boric acid, and 25 ml. of a
solution containing 40 p.p.m. boron was added to the 400 gm. of soil to make
at least 2.5 p.p.m. boron in the soil at the time the plants were first watered.
Treatments were made a little at a time until a sufficient quantity of the
nutrient, usually a total of about 1 liter, had been added.   Most of the nu-
trient was added during the first half of a 6- to 10-week growth period.   Sun-
flower was used as the indicator plant to determine responses from the differ-
ent nutrient combinations.   The plan was to supply an abundance of every-
thing except the one element for which the availability was tested.

In the field, cover crop response to fertilizers was studied on plots 10 feet
square treated with fertilizers at the prescribed rates.   The fertilizer was
broadcast on the surface of the soil in the fall usually after the cover crop had
come up.   Cover crop yields and responses were obtained by sampling and
drying 0.0001 acre from each plot, and comparing with suitable untreated
checks.   With this method, treated plots need not be adjacent, as each treated
plot is best compared with the surrounding untreated crop.   By taking small
plots it is possible to have many replications representing a greater variety
of soils and conditions.   The small plots eliminate much of the error due to
soil variability.   Only large differences in yield are considered significant.

Many soils unreported in this paper have been tested by the procedures here
presented.   The results on the soils that are reported are typical of a great
mass of data, which would only lead to repetition if reported.   For example,
in the greenhouse a total of more than 20,000 individual samples of soils pro-
ducing plants have been studied during the last 3 years.   These studies in-
clude the principal soils devoted to nut production in this state.

SOILS

Newberg loam is a recent soil formation, usually occurring along river banks.
The surface is rolling or billowy and characterized by long low ridges.   Drain-
age is good to excessive.   The surface layers of loam may be 8 to 18 inches
deep, underlain by stratified sediments ranging from fine sandy loam to sandy
loam or sand.   The amount of sand and the coarseness of texture usually
increase with depth.   The land is subject to flooding by high water.   The
silt loam is very similar to the loam except in texture.   Typical soils are fairly
productive.

Amity silt loam is an old valley-filling formation.   The surface soil is brown,

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[3] A mixture of the above solutions supplied nitrogen, phosphorus, sulfur, potassium,
calcium, and magnesium, once called "a complete nutrient solution." In this report the
mixed solution is designated "the basal nutrient."

or grayish brown, slightly mottled and 12 to 20 inches deep. The upper sub-surface soil is brownish gray or brown clay loam, highly mottled, slightly compact, but also slightly granular in structure. The deeper subsurface soil between 25 and 46 inches is grayish brown or yellowish brown, highly mottled, friable clay loam, less compact than the layer above. The surface is flat or slightly undulating. Drainage is usually poor, but productivity is good for cereal and hay crops.

Salkum clay loam is an old valley-filling soil on the higher elevations of the valley floor. The surface 8 to 12 inches is brown, slightly compact clay loam with a yellowish cast. The subsurface soil to a depth of 18 to 24 inches is brown or reddish brown rather compact clay loam. Below this depth the soil is grayish brown or reddish brown and full of soft, water-worn gravels, highly weathered and easily cut with a knife. Below about 30 inches the proportion of gravel increases, and the soil is more compact than the layers above. The soil is only moderately productive.

Aiken clay loam is brownish red or red heavy soil to a depth of about 16 inches. The structure is usually granular and permeable. The subsurface soil to a depth of about 3 feet is dull red, rather compact clay. The lower depths grade into bedrock of basalt. The soils are known locally as the "red hill soils." They are not highly productive.

Sites clay is another of the "red hill soils" formed from sedimentary rocks. The surface soil is brownish red or red and granular in structure to a depth of 8 to 12 inches. Below this the red soil is somewhat compact to a depth of 18 to 22 inches, gradually becoming moderately dense. The depth to sand-stone or shale is 36 to 100 inches, in the area studied. The soil is similar to Aiken clay loam in productive capacity.

RESULTS

Physical properties of soils

Some of the important physical soil properties affecting plant growth are texture, structure, and depth. These properties influence moisture capacity, usable water, drainage, aeration, root penetration, and the capacity of the root system to function normally in the absorption of moisture and nutrients.

Newberg loam, supporting a walnut orchard (table 1), has favorable physical properties throughout a deep profile. There is enough fine silt and clay to give body to the soil and to hold moisture and nutrients. There are no obstructing layers. This particular locality, however, has sandy spots that are drouthy. At a depth of 7 or more feet the soil becomes very sandy. The only data obtained beyond this depth were on the root distribution of walnut. The average field moisture capacity of 29 per cent and the average wilting point of 15 per cent, giving 14 per cent of usable water for a 6-foot profile, compare favorably with those for the better soils devoted to nut culture. Salkum silty clay loam has a high moisture-holding capacity and carries a large percentage

TABLE 1

Physical properties, moisture relationships, and root distribution in typical orchard soils

SOIL LAYER	FINE SILT AND CLAY	TOTAL POROSITY	MOISTURE AT FIELD CAPACITY	CAPILLARY POROSITY VOLUME	NONCAPILLARY POROSITY VOLUME	WILTING COEFFICIENT	USABLE WATER	ROOT DISTRIBUTION
feet	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Newberg loam								
0–½	37.3	53.5	30.6	38.6	14.9	16.3	14.3	1.6
½–1	34.3	54.6	30.6	37.6	17.0	16.3	14.3	17.7
1–2	26.3	57.3	32.5	38.0	19.3	17.5	15.0	24.2
2–3	26.7	60.2	32.8	35.8	17.0	16.7	16.1	7.9
3–4	16.3	57.8	27.0	31.3	26.5	13.1	13.9	3.8
4–5	28.1	58.9	26.8	30.3	28.6	13.6	13.2	11.5
5–6	19.3	59.2	23.0	25.8	23.4	12.2	10.8	3.7
6–7	....	....	....	....	....	....	....	9.4
7–8	....	....	....	....	....	....	....	11.0
8–9	....	....	....	....	....	....	....	2.4
9–10	....	....	....	....	....	....	....	6.8
Average....	26.9	57.3	29.0	33.9	20.9	15.1	13.9	9.1
Salkum silty clay loam								
0–½	48.8	52.8	35.9	45.6	7.2	15.8	20.1	Cultivated
½–1	53.8	52.7	35.9	46.3	6.4	15.8	20.1	38.0
1–2	66.2	50.7	34.8	46.6	4.1	14.0	20.8	27.4
2–3	67.2	56.1	39.3	46.9	9.2	26.0	13.3	18.3
3–4	51.8	57.9	50.4	57.5	0.4	21.8	28.6	15.2
4–5	52.3	60.2	53.0	56.7	3.5	21.9	31.1	0.3
5–6	44.6	62.7	61.0	61.0	1.7	23.3	37.7	0.0
6–7	38.2	59.4	51.5	55.6	....	....	....	0.5
7–8	49.8	60.5	53.0	55.6	....	....	....	0.1
8–9	43.6	59.9	53.3	57.0	....	....	....	0.2
Average....	51.6	57.3	46.8	52.9	4.6	19.8	24.5	11.1
Sites clay								
0–1	66.4	55	35	43	12	22	13	8.1
1–2	71.3	57	36	43	14	23	13	30.0
2–3	70.3	57	40	49	8	26	14	31.7
3–4	82.3	57	42	52	5	30	12	21.3
4–5	70.3	58	49	58	0	32	17	5.2
5–6	70.0	58	50	60	−2	44	6	0.7
6–7	64.6	55	42	51	4	....	....	0.6
7–8	56.6	58	46	52	6	....	....	2.4
Average....	68.9	56.8	42.5	51.0	5.9	29.5	12.5	12.5

of supposedly usable water. Other properties, however, are unfavorable in this soil and much of the moisture is unavailable to the crop. This soil is typical of those that have not proved satisfactory for nut culture.

At the present time there is no method for adequately measuring soil structure. From the practical standpoint, the determination of the distribution of the pore space into capillary and noncapillary portions has considerable value (2). Capillary porosity gives moisture-holding capacity to the soil. Noncapillary porosity provides for aeration or oxidation and a condition favorable to root penetration and development, making possible the utilization of the soil moisture by the crop. Water penetrates the soil through noncapillary openings and is absorbed and held by the capillary pores as capillary water. When the capillary capacity of the soil is satisfied, any excess water drains away by gravity through noncapillary openings. Roots likewise penetrate and develop principally in noncapillary spaces. Soils with few or no noncapillary openings allow only sparse root development with few fine roots and root hairs for absorption. The sparsity of roots in the Salkum soil is characteristic of soils lacking in noncapillary porosity. Trees on this type of soil may wilt when the deep soil still has a large supply of moisture. This relationship is brought out by comparing the data (table 1) for the noncapillary porosity and the root distribution in the Newberg and Salkum soils, the one well suited and supporting a good walnut orchard, the other unfit and a failure for orchard production.

Both the Salkum and the Sites soils show a considerable increase of fine material in the subsoils, a condition pointed out by Oskamp and Batjer (4) as unfavorable to drainage, aeration, and root development in orchards. The senior author has found poor root development and poor moisture usage in soils of this character (5). Soils such as the Newberg, which show no tendency for the clay to concentrate in any horizon, have permitted good root development and penetration and the efficient use of soil moisture.

Available nutrients in the soil

Availability of nutrients in the root zone is an important factor in plant growth. Chemical methods determine totals present rather accurately, and certain types of chemical methods have been used with a degree of success to indicate availability. "Solubility," however, is the term preferred by some for the results obtained by the use of common soil-testing methods.

The data of table 2 indicate that the largest supply of water-soluble nutrients is in the surface soil. The quantity of water-soluble nutrients present is positively correlated with the distribution of organic matter, until a depth below the principal feeding root zone is reached, even though the trees were growing and absorbing nutrients at the time the samples were taken.

When stronger solvents are used there is less difference in the amount of soluble nutrients in the different soil layers. In most of the soils studied, more acid-soluble as well as water-soluble potassium has been found in the

TABLE 2

Distribution of soluble nutrients and organic matter in the profiles of typical orchard soils

SOIL LAYER	ORGANIC MATTER	AVAILABLE* P	WATER-SOLUBLE K	WATER-SOLUBLE Ca	K SOLUBLE IN 0.05 N HCl	Ca SOLUBLE IN 0.05 N HCl
feet	*per cent*	*p.p.m.*	*p.p.m.*	*p.p.m.*	*m.e./100 gm.*	*m.e./100 gm.*
Newberg silt loam						
0–½	3.03	195	34.6	....	1.52	25.75
½–1	1.20	130	22.4	41.0	0.96	25.24
1–2	0.58	112	4.9	19.0	0.41	24.38
2–3	0.51	142	1.8	18.0	0.41	25.53
3–4	0.40	120	1.1	11.0	0.37	19.33
4–5	0.37	120	....	9.0	0.46	20.35
5–6	0.30	130	....	15.0	0.25	22.88
6–7	0.27	142	....	12.0	0.34	22.58
7–8	0.21	142	....	12.0	0.30	23.10
8–9	0.10	104	....	15.0	0.36	24.16
Amity silty clay loam						
0–½	3.71	91	29.4	132	0.45	9.84
½–1	2.93	80	7.7	99	0.37	12.20
1–2	1.51	77	7.1	65	0.44	12.78
2–3	0.34	96	1.7	14	0.45	16.93
3–4	0.29	213	1.7	4	0.50	18.98
4–5	0.25	213	1.1	2	0.39	15.49
5–6	....	237	1.0	2	0.50	17.99
6–7	0.20	128	8.0	2	0.41	14.49
7–8	0.09	68	15.8	42	0.45	28.29
8–9	0.07	48	16.9	63	0.47	36.68
9–10	0.07	36	20.9	69	0.54	46.15
Sites clay						
0–½	4.67	7	21.4	107	0.69	7.65
½–1	3.62	9	14.2	104	0.38	6.43
1–2	2.27	10	7.4	55	0.27	0.45
2–3	1.33	8	2.3	25	0.22	0.28
3–4	0.79	7	3.0	21	0.26	0.23
4–5	0.56	5	2.5	8	0.24	0.22
5–6	0.48	8	0.7	3	0.24	0.22
6–7	0.33	12	0.5	3	0.28	0.26
Aiken clay loam						
0–½	3.74	12	51.0	119	1.01	7.47
½–1	2.04	7	18.0	87	0.74	6.20
1–2	1.43	7	2.6	40	0.15	5.03
2–3	0.95	21	0.3	26	0.16	4.03
3–4	....	...	....	18	....	4.61

* P soluble in buffered 0.002 N H_2SO_4 (Truog method) as reported in reference (6).

surface soil than was found deeper. This may be due to the continual return of organic materials carrying relatively large amounts of potassium to the surface soil. Acid-soluble phosphorus and calcium are well distributed throughout the entire soil profile.

The Newberg soil is rather well supplied with nutrients and possesses favorable physical properties. The Amity has a fair supply of nutrients but is inclined to have a tight clay subsoil and is not well suited to orchards. The supply of nutrients in the Sites soil is only fair. Available phosphorus is low. Only the deeper phases of this soil support successful orchards.

The greatest contrast in nutrient content is between the residual hill soils and the recent river bottom soils. The latter are particularly well supplied with easily available calcium, whereas the former are commonly very low in their supply of this element. The supply of calcium is much larger in the surface foot in the hill formations than at greater depths. Below the top 2 feet the Sites has only about one-tenth as much easily soluble calcium as the Newberg soil.

The contrast between the hill and the river bottom soils is even greater with respect to available phosphorus. The examples given are typical of results obtained on many other soils. This is an outstanding example, however, of the weakness of chemical methods. Greenhouse trials show much less difference in the capacity of such soils as the Aiken and the Sites to supply phosphorus to the plant, when compared with the good soils of which the Newberg is typical.

The old valley-filling soils such as the Amity are usually intermediate between the river bottom and the hill soils both in their supply of nutrients and in their capacity to produce crops. The better old valley-filling soils may be nearly as productive as the river bottom soils. Yield differences between good and poor soils in the greenhouse are usually less than chemical data would indicate and also less than the differences which occur in the field. The handicap of lack of depth, of impermeable structure, of the presence of claypans, and of poor aeration is partly overcome when the soil is placed in the greenhouse under controlled conditions. The poor soils therefore make a much better relative showing in the greenhouse than in the field.

Greenhouse studies

Available nutrient materials at different depths in a 9-foot Newberg soil profile, as measured by the capacity of the soil to support growth of sunflowers, are indicated by the data of table 3. The data show that the surface 2 feet are capable of contributing most nutrient for plant growth. Below this depth there is a gradual decrease in the capacity of the soil to support plants. Nitrogen is probably the most important limiting nutrient element, sulfur next, phosphorus next, and then potassium. Lack of available boron limits growth in most soils, particularly when other nutrients are supplied in adequate amounts. The greenhouse procedure has been valuable for bringing out sulfur

deficiency, which in many soils is nearly as great as the deficiency of phosphorus. No satisfactory chemical method for determining available sulfur has been developed. Compost to a large extent corrects all deficiencies. This highly fertile river bottom soil supports a very productive filbert orchard.

The data of table 4 indicate plant growth for similar depths of Aiken clay loam, a hill soil less fertile than the Newberg. The top two or three feet contribute most nutrients to the plant, but in some cases where no supplemental nutrient is used even the 5-foot horizon is nearly as good. In this soil nitrogen is the most important limiting nutrient element for sunflower growth, phosphorus next, then potassium, and last sulfur. Lack of available boron is

TABLE 3

Dry weights of 10 sunflower plants grown in Newberg loam soil with various treatments

TREATMENT	1 FT.	2 FT.	3 FT.	4 FT.	5 FT.	6 FT.	7 FT.	8 FT.	9 FT.	TOTAL
	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.
Check....................	9.7	9.1	6.9	6.7	6.2	5.9	5.7	4.9	4.5	59.6
Basal nutrient..............	28.6	25.3	14.5	14.2	14.3	13.6	11.4	11.3	11.1	144.3
Basal nutrient and B........	28.3	28.3	29.0	28.3	27.9	28.9	30.7	30.5	27.6	259.5
K omitted.................	13.9	11.3	5.4	6.9	5.9	4.6	4.4	4.0	4.6	61.0
K omitted and B added.....	11.8	11.5	9.7	9.5	8.3	8.9	8.4	8.8	8.4	85.3
N omitted.................	5.2	3.8	4.3	4.2	4.6	3.8	3.8	3.5	3.1	36.3
N omitted and B added.....	5.1	4.5	3.8	4.7	4.2	3.4	4.2	4.4	4.1	38.4
P omitted.................	9.6	8.7	7.4	7.0	7.4	6.0	5.6	5.3	5.5	62.5
P omitted and B added......	9.5	7.5	8.3	8.5	8.6	7.7	8.4	8.3	7.6	74.4
S omitted.................	6.0	4.8	5.0	5.2	5.0	4.2	4.2	4.7	5.0	44.1
S omitted and B added......	5.0	4.6	4.1	5.5	4.6	4.1	4.4	4.8	5.5	42.6
Compost..................	20.6	20.2	21.1	19.5	20.1	23.5	25.9	....	17.9	168.8
Total..................	153.3	139.6	119.5	120.2	117.1	114.6	117.1	90.5	104.9	
No B..................	63.3	53.9	36.6	37.5	37.2	32.2	29.4	28.8	29.3	
B.,....................	59.7	56.4	54.9	56.5	53.6	53.0	56.1	56.8	53.2	
Difference..............	−3.6	2.5	18.3	19.0	16.4	20.8	26.7	28.0	23.9	

an important growth factor in the soil from the deeper layers when other nutrients are supplied. Compost is very effective in supplying all nutrients including boron.

The Sites is probably somewhat less productive in the field than the Aiken soil. Both chemical tests and greenhouse trials indicate that it needs complete fertilization. The omission of phosphorus, potassium, sulfur, or boron causes a marked reduction in yield, as indicated by the data of table 5.

At present field data are available only for the Aiken soil. There field results, in general, corroborate the results of greenhouse studies.

The data of tables 3, 4, and 5 indicate the futility of trying to raise the productive capacity of these soils to a high level as long as any one important nutrient element is deficient.

TABLE 4

Dry weights of 10 sunflower plants grown in Aiken clay loam soil with various treatments

TREATMENT	0–½ FT.	½–1 FT.	2 FT.	3 FT.	4 FT.	5 FT.	6 FT.	7 FT.	8 FT.	9 FT.	TOTAL
	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.
Check...........	2.79	2.75	2.42	2.07	2.00	2.25	1.61	1.41	1.29	1.27	19.8
Boron...........	2.96	3.21	3.10	2.36	2.15	2.26	1.39	1.76	1.54	1.46	22.1
Basal nutrient.....	9.49	9.90	9.28	8.11	6.32	9.78	6.39	5.54	5.54	4.05	74.4
Basal nutrient and B.............	9.29	9.88	10.22	9.86	10.93	10.29	10.46	10.40	10.44	9.30	101.1
S omitted........	9.00	9.85	9.18	7.79	5.44	6.52	4.17	5.31	3.99	3.63	65.9
S omitted and B added.........	....	9.60	9.71	8.95	6.87	7.56	8.83	9.48	8.98	9.16	79.1
K omitted........	10.3	7.36	7.23	5.36	5.33	....	3.71	2.91	2.52	2.27	46.7
K omitted and B added.........	8.56	6.02	7.35	5.05	5.23	5.07	7.31	4.85	5.27	4.36	59.1
P omitted........	5.12	4.40	4.84	5.28	4.55	4.98	4.20	3.85	3.83	3.43	44.5
P omitted and B added.........	5.35	5.20	5.40	4.77	5.00	5.45	5.27	5.93	4.91	4.90	52.2
N omitted........	5.44	5.13	4.76	4.85	3.28	4.96	2.69	2.64	2.37	2.88	39.0
N omitted and B added.........	4.81	4.99	4.84	4.82	3.01	5.39	3.21	3.36	3.45	2.29	40.2
N only...........	3.84	3.63	3.69	3.16	2.97	3.32	3.01	2.39	1.69	1.85	29.5
N only B added...	3.95	4.07	3.60	3.29	3.03	2.89	3.15	3.87	2.14	2.51	32.5
Compost.........	13.28	13.18	13.88	11.50	12.10	11.20	10.90	11.51	11.29	10.60	119.4
Compost and B added.........	13.24	13.52	13.08	12.72	12.23	12.35	12.33	12.40	11.80	11.78	125.4
Lime............	3.07	2.77	2.10	1.98	1.19	1.47	1.01	0.88	0.97	0.86	16.3
Lime and B......	2.24	2.88	3.46	2.55	1.67	2.16	1.77	1.78	1.85	1.77	22.1
Total.........	112.73	118.34	118.14	114.47	93.30	97.89	92.95	90.27	83.77	78.38	

TABLE 5

Dry weight of 10 sunflower plants grown in Sites clay soil with various treatments

TREATMENT	0–½ FT.	½–1 FT.	2 FT.	3 FT.	4 FT.	5 FT.	6 FT.	7 FT.	8 FT.	9 FT.	10 FT.	TOTAL
	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.
Check...................	4.2	3.4	3.3	2.4	2.0	1.4	1.3	1.0	1.0	1.0	1.0	22.0
Boron..................	4.2	4.5	3.8	2.1	2.2	1.6	1.7	1.5	1.5	1.3	1.2	25.6
Basal nutrient............	12.0	9.0	11.0	9.1	8.3	4.8	4.5	3.9	3.6	4.5	4.1	74.8
Basal nutrient and B.......	12.5	10.2	12.2	11.3	11.6	9.8	10.9	9.2	7.3	7.7	6.7	119.4
Compost.................	8.0	7.6	6.0	5.7	11.0	11.5	10.9	11.1	7.6	11.7	12.2	103.3
Compost and B...........	7.5	6.9	5.8	6.2	10.6	11.5	10.2	11.6	10.6	11.4	11.8	104.1
K omitted...............	8.9	7.6	5.1	5.3	4.9	4.5	3.8	3.0	3.0	2.3	2.6	51.0
K omitted and B added....	9.9	8.0	7.2	6.4	5.5	4.8	4.5	5.0	4.3	4.0	4.5	64.1
P omitted...............	8.6	7.7	6.6	7.0	4.7	4.5	4.5	3.3	4.1	3.5	3.2	57.7
P omitted and B added.....	7.9	5.3	7.1	6.4	5.7	5.4	5.5	4.2	5.2	5.3	4.7	52.7
S omitted...............	9.9	8.0	8.9	8.7	6.5	4.6	4.1	4.4	3.4	2.7	3.0	64.2
S omitted and B added.....	10.7	10.3	11.1	9.6	7.6	6.1	5.5	5.8	4.9	4.3	4.4	80.3
Total..................	104.3	88.5	88.1	80.2	80.6	70.5	67.4	64.0	56.5	59.7	59.4	
No B..................	51.6	43.3	40.9	38.2	37.4	31.3	29.1	26.7	22.7	25.7	26.1	
B.....................	52.7	45.2	47.2	42.0	43.2	39.2	38.3	37.3	33.8	34.0	33.3	
Difference..............	1.1	1.9	6.3	3.8	5.8	7.9	9.2	10.6	11.1	8.3	7.2	

TABLE 6

Distribution of available boron in the soil profile, as indicated by the dry weight of 30 sunflower plants

SOIL	DEPTHS*	TREATMENT	CHECK	BASAL NUTRIENT	S OMITTED	K OMITTED	P OMITTED	N OMITTED	N ONLY	COMPOST	LIME	RATIO† B/NO B
	feet		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
Aiken clay loam	0–⅓	No B	7.96	28.67	28.03	24.61	14.39	12.33	11.16	40.34	7.84	
	⅓–1	B	9.27	29.39	29.31	21.39	15.95	14.64	11.62	39.83	8.58	1.03
	1–2	Difference	1.31	0.72	1.28	−3.22	1.56	2.31	0.46	−0.51	0.74	
	3–4	No B	5.85	22.48	17.13	14.11	13.73	10.93	9.30	34.20	3.67	
	4–5	B	6.33	31.67	23.26	17.62	16.72	11.61	9.06	36.90	5.61	1.25
	5–6	Difference	0.48	9.19	6.13	3.51	2.99	0.68	−0.24	2.70	1.94	
	6–7	No B	3.93	15.13	12.93	7.70	11.11	7.89	5.93	33.40	2.70	
	7–8	B	4.76	30.14	27.62	14.48	15.73	9.10	8.52	35.97	5.40	1.71
	8–9	Difference	0.83	15.01	14.69	6.78	4.62	1.21	2.59	2.57	2.70	
Amity silty clay loam	0–⅓	No B	6.84	13.77	8.29	12.28	10.42	8.60	7.93	19.90	5.56	
	⅓–1	B	6.18	26.98	8.90	17.60	11.91	9.68	8.36	20.33	6.31	1.30
	1–2	Difference	−0.66	13.21	0.61	5.32	1.49	1.08	0.43	0.43	0.75	
	3–4	No B	5.00	7.51	5.35	8.78	6.74	5.55	5.02	21.29	4.48	
	4–5	B	5.76	28.73	5.67	19.20	15.52	7.46	6.12	20.41	5.79	1.94
	5–6	Difference	0.76	21.22	0.32	10.42	8.78	1.91	1.10	−0.88	1.31	
	7–8	No B	5.13	8.02	7.27	9.02	6.65	5.50	5.54	19.05	5.62	
	8–9	B	7.05	26.77	10.36	19.77	12.81	7.56	8.24	19.11	6.70	1.88
	9–10	Difference	1.92	18.75	3.09	10.75	6.16	2.06	2.70	0.06	1.08	

* In each case, the yield on a sample of each of the three horizons is added together.
† The compost treatment was not included in figuring the ratios.

The effectiveness of compost in correcting all deficiencies indicates the importance of humus renewal in building up and maintaining all the soils. The use of nitrogen fertilizers alone, on the other hand, often gives unsatisfactory results. The lack of response from nitrogen alone is characteristic of many trials not here reported.

The distribution of available boron in two soil profiles is brought out by the data of table 6. In each case the yield of sunflowers on a sample of each of three horizons is added together and the boron and no boron treatments are compared. The data indicate that boron deficiency increases decidedly with soil depth. The data indicate also that boron deficiency can be scarcely observed until other nutrients are supplied to stimulate increased plant growth. Those treatments that give the greatest growth of plants, also show the largest difference between the boron and no boron treatments.

The authors postulate that the greater amount of available boron in the surface soil is due to the organic matter. Vegetation and soils develop together over a period of years. A residue of humus that may amount to 200,000 or more pounds per acre accumulates in the surface 2 feet. In this humus residue much of the boron is found in organic form and is more available to the plant through decomposition processes than are the mineral forms of boron found in the deep soil. The efficacy of compost and other organic materials in correcting boron deficiency is evidence of the truth of the postulation.

Field trials

Regardless of what chemical or greenhouse tests may indicate, results in the field are most important. When translated into farm practice, only those fertilizers showing economic returns will receive much attention. Lack of control under field conditions, however, makes it difficult to interpret field trials and sometimes leaves an open question as to the reason for certain responses.

The data of table 7 give the field results on cover crops grown on the same Aiken clay loam used to obtain the data in tables 4 and 6. Superphosphate gave no significant response on barley and vetch as a cover crop. Calcium nitrate gave some increased growth, with little additional response when gypsum was added. The best response was from ammophos, indicating that nitrogen and phosphorus are important to the growth of cover crops. The presence of an appreciable but undetermined amount of sulfur in the ammophos makes it impossible to say to what extent the good returns from ammophos may be influenced by the sulfur contained. Likewise boron as an impurity in the ammophos made it impossible to check the response from this element. A boron-treated series, unreported here, showed no increase from the additional boron supplied. There was no appreciable response when potash was added to the ammophos on this soil.

The data in table 8 indicate the response from fertilizers, of barley and vetch as a cover crop, on a soil much like Salkum clay loam. In this case nitrate

produced a marked response in cover crop growth. Ammophos, as before, produced the best yield, and applications of potash showed little or no increase in growth. The good response from stable manure indicates the value of

TABLE 7

Effect of fertilizer on growth of barley and vetch as a cover crop on Aiken clay loam

TREATMENT	ACRE RATE OF TREATMENT	ACRE YIELD DRY WEIGHT	YIELD INCREASE	
	lbs.	lbs.	lbs.	per cent
Check.................................	...	791	.....	...
Calcium nitrate.........................	653	2,075	1,284	162
Calcium nitrate.........................	653			
Gypsum................................	314	2,520	1,729	218
Ammophos 16–20–0.....................	697	3,354	2,563	324
Ammophos 16–20–0.....................	697			
Gypsum................................	314	3,777	2,986	377
Ammophos 16–20–0.....................	697			
Muriate of potash......................	200	3,828	3,037	384
Superphosphate 0–18–0..................	871	862	71	9

TABLE 8

Effect of fertilizer on growth of barley and vetch as a cover crop

TREATMENT	ACRE RATE OF TREATMENT	ACRE YIELD DRY WEIGHT	YIELD INCREASE	
	lbs.	lbs.	lbs.	per cent
Check.................................	...	1,241	.....	...
Calcium nitrate.........................	653	4,893	3,652	294
Calcium nitrate.........................	653			
Gypsum................................	314	4,110	2,869	231
Ammophos 16–20–0.....................	697	7,711	6,470	521
Ammophos 16–20–0.....................	697			
Gypsum................................	314	7,316	6,075	490
Ammophos 16–20–0.....................	697			
Gypsum................................	314	7,457	6,216	501
Muriate of potash......................	200			
Superphosphate 0–18–0..................	871	2,811	1,570	127
Manure................................	10†	5,038	3,797	306
Manure................................	10†			
Superphosphate 0–18–0..................	871	8,189	6,948	560

* Soil unsurveyed and unidentified but much like Salkum clay loam.
† Tons.

organic materials and humus renewal in this soil. Manure and superphosphate combined gave the best yields of any treatment.

The data of table 9 indicate the difficulty of obtaining consistent and reliable results from fertilizer applications on cover crops under field conditions. The

yields of duplicate plots vary widely in some cases. On Aiken silty clay loam soil, only the treatments that provide nitrogen in the ammonia form show much effect on cover crop growth, and this was mostly on the barley. Possibly the

TABLE 9

Effect of rate of fertilizer application on mixed barley and vetch cover crop growth on Aiken silty clay loam soil

TREATMENT	FULL RATE OF TREATMENT PER ACRE	DRY WEIGHT YIELDS AT DIFFERENT RATES OF TREATMENT		
		Full rate	Half rate	Quarter rate
	lbs.	lbs.	lbs.	lbs.
Check......................	...	*a. 1,418	....	.....
		b. 1,766	b. 1,240	1,153
Treble phosphate................	321	a. 1,317	a. 832	1,384
Gypsum......................	312	b. 1,002	b. 1,174	
Treble phosphate................	321	a. 1,969	a. 1,805	1,114
Gypsum......................	312	b. 1,816	b. 1,883	
Sodium nitrate...................	694			
Ammophos, 11–48–10............	989	a. 3,220	a. 2,112	2,055
		b. 4,410	b. 1,940	
Ammophos, 11–48–0.............	989	a. 2,415	a. 1,871	1,781
Gypsum......................	312	b. 2,750	b. 2,640	
Ammophos, 11–48–0.............	989	a. 3,863	a. 3,556	1,116
Gypsum......................	312	b. 5,812	b. 2,704	
Muriate of potash..............	200			
Ammonium sulfate..............	520	a. 3,986	a. 2,041	1,249
		b. 3,233	b. 1,958	
Ammonium sulfate..............	520	a. 2,878	a. 2,962	1,536
Treble phosphate................	321	b. 4,072	b. 2,684	
Ammonium sulfate..............	520	a. 4,326	a. 3,317	1,805
Treble phosphate................	321	b. 4,415	b. 2,695	
Muriate of potash..............	200			
Superphosphate 18 per cent.......	653	a. 1,547	a. 1,373	902
		b. 1,450	b. 1,653	
Superphosphate.................	653	a. 1,969	a. 1,852	1,375
Sodium nitrate..................	694	b. 2,110	b. 1,624	
Superphosphate.................	653	a. 2,183	a. 1,105	710
Sodium nitrate..................	694	b. 1,487	b. 3,225	
Gypsum......................	312			
Superphosphate.................	653	a. 2,713	a. 1,490	1,275
Sodium nitrate..................	694	b. 1,057	b. 1,258	
Gypsum......................	312			
Muriate of potash..............	200			

* a and b indicate duplicate plots.

nitrate form of nitrogen leaches and is lost before the crop can use it. A nitrogen, phosphorus, potash and sulfur combination gave the greatest growth. Ammophos, not only on this soil but on many others unreported, has been

consistent in giving a good response. Neither sulfur nor potash carriers appear very consistent on this soil in the responses obtained.

The primary purpose of this study was to obtain data on rates of fertilization. With allowance for inconsistencies, the half rate has given rather good responses when a response was obtained from the full rate of application. In most cases the quarter rate has shown little effect. In several unreported trials similar to this, cover crop growth has been greatest with the full rate of fertilization, but no appreciable increase over the checks was obtained with the quarter rate. These results are all from fall applications of fertilizer. Sufficient data are not available yet for reporting results of spring applications.

DISCUSSION

The data, presented from typical areas, indicate that the better soils contain more easily soluble plant nutrients than the poorer soils. Such reliability as the quick chemical tests may possess, undoubtedly rests upon this fact. A good supply of essential nutrients is not sufficient, however, to assure satisfactory production in nut orchards: the physical character of the root zone and of the soil profile is equally important.

Physical properties are important because of their relation to root development and the proper functioning of the roots in the nutrition of the plant. Adequate noncapillary porosity for drainage, aeration, and root penetration is necessary. Effective soil depth is the depth to which roots are able to penetrate and function normally. Tight subsoils and claypans may limit soil depth as effectively as bedrock.

There is little point to a fertilizer program on soils that are physically unsuited for crop production. No system of fertilization, however adequate the supply of plant nutrients, can counteract a bad physical condition such as a tight subsoil or lack of depth. The first requisite to the successful use of fertilizers is a soil with physical properties that adapt the soil to the crop that is produced. A soil such as Sites clay which has unfavorable properties, both physical and chemical, is not highly valuable for most cultivated crops (tables 1, 2, and 5). A walnut orchard on this soil is a complete failure. Grain had failed before the land was planted to walnuts. Availability of nutrients to plants is contingent upon the presence of roots and also upon the ability of the roots to function in absorbing those nutrients. McGeorge (3) has shown that roots may be present but unable to function after a waterlogged condition has developed. Roots in a waterlogged soil in the presence of an abundance of moisture may fail to absorb sufficient moisture to meet transpiration needs.

Even in good soils most of the nutrients for the growing plant probably come from the surface layers. The deep soil serves to supply moisture principally through the deep portions of the root system. Shallow-rooted crops, therefore, may thrive on wet soils if there is moisture in the upper portion during the growing season. Deep-rooted plants, such as walnuts, that produce their crops during the months of dry weather in the Pacific Northwest, are dependent

upon stored soil moisture. Probably eight or ten feet of soil depth is necessary to allow sufficient soil volume and moisture storage, since only storage in the root zone is of much help.

When plants are grown in the greenhouse on samples of soil taken at different depths, the best growth is obtained from the surface two or three feet. Below that point the amount of growth gradually diminishes as the soil is taken from greater depths. This gives some idea of the portion of the soil profile that is capable of contributing nutrients for plant growth. It is noticeable also that the surface horizons are more responsive to nutrient additions, except those of boron. Soil from the deeper layers may show a large percentage increase, but total growth is small, without boron. Boron is so decidedly the limiting nutrient element for sunflower growth in soil from the deeper layers that plant response from other nutrients is contingent upon the correction of the boron deficiency.

In field trials nitrogen and phosphorus combinations, in which the nitrogen was in the ammonia form, have given good results consistently, especially on nonlegumes. Sulfur in addition to the nitrogen and phosphorus may or may not show a response on the cover crop. On the basis of the consistent response from sulfur compounds in the greenhouse with sunflower as the indicator plant, the probability of a sulfur deficiency that might limit orchard production deserves serious consideration. Likewise the seriousness of the boron deficiency needs further study.

The efficiency of compost and other organic materials for correcting nutrient deficiencies in the soil indicates the importance of providing for adequate humus renewal. Annual cover crops, stable manure, waste hay, and compost may well be utilized for soil improvement. To date, however, no system of fertilization or management appears to offer much compensation for lack of depth and aeration of the soil. The physical nature of the soil profile is just as important as the chemical.

When the soil is physically suited to deep-rooted orchard crops, the adequacy of the fertilizer program becomes important. The average orchardist on good soil can probably well afford to practice both more liberal and more complete fertilization than is commonly practiced. Over a period of years a fertilizer program which assures satisfactory cover crop growth probably will give satisfactory results with the trees (1).

After a study of several thousand samples of soil in the laboratory, greenhouse, and field, only a few tentative conclusions seem justified. Grains or grasses in the orchard must have a fertilizer that furnishes nitrogen, in nearly all cases the most important limiting nutrient element. Nonlegumes are likely to respond to phosphorus, and sometimes to sulfur, used with the nitrogen. Legumes such as vetch, if fertilized, probably should receive a phosphorus and sulfur combination with the nitrogen omitted. Vetch, unless grown nearly to maturity, has not shown much response from any fertilizer. When grain and vetch are grown together liberal use of nitrogen fertilizer may

stimulate the grain sufficiently to smother the legume. Not infrequently the nitrogen-phosphorus combination of fertilizer stimulates weeds to such an extent that nearly the entire planted cover crop is smothered. Chickweed, which grows vigorously in the fall and dies in the winter, has been a particular offender in this respect. Some of the inconsistences in the field data are due to the aforementioned responses.

Probably not quite the same results are obtained in the fertilization of crops grown for cover as would follow if the same crops were grown to produce grain or seed. In Western Oregon, without irrigation and with little summer rain, orchard cover crops must be worked down early, often the first part of April, to save moisture. The chief object in fertilization, therefore, is to produce a large vegetative growth early in the season. Neither superphosphate nor treble phosphate has shown any appreciable effect when used alone for this purpose even on vetch. If used to produce grain or vetch seed, the results might be quite different.

In general, greenhouse studies have been more useful than chemical methods for detecting soil deficiencies. In view of the difficulty of controlling field conditions such as soil moisture and temperature and of the competition with weeds which affect the growth of the cover crop, greenhouse studies have been more satisfactory than field plot trials. The latter are essential, however, for a complete study.

Only long-time trials in the field, extending through at least several years of the life of the orchard, can definitely determine the responses from fertilizers used under field conditions. The use of the physiologically acid fertilizers such as ammophos and sulfate of ammonia gives excellent results for a time, in fact, the best results obtained thus far. But what will be the effect after several years, when a gradually accumulating acidity may attain injurious proportions in the soil? Probably a liming program will become necessary to correct the acidity. Only a prolonged program of study can provide the necessary information for handling such problems.

There appears to be a definite advantage in using a small portion rather than a larger bulk of soil for the greenhouse studies. With little soil and liberal use of all nutrients except one, the growing plant easily exhausts the supply of the one nutrient which must be obtained entirely from the soil. This procedure makes it possible to accentuate deficiencies in such a way that the relative seriousness of the deficiency may be estimated. This method measures the nutrient-supplying power of the soil for the individual nutrient with any particular plant.

There is also an advantage in using small and somewhat temporary field plots to give opportunity for many replications and to eliminate, to some extent, the difficulty of dealing with soil variability. Responses are as definite on an area of 100 square feet as on an acre. Unless the treatments double the yields, the responses from the fertilizers are probably of little significance. The expense of field trials is greatly reduced by using small plots that may be

easily continued or abandoned according to circumstances. This type of work is largely of exploratory nature, the results of which may be used in ultimately setting up more permanent long-time trials that may be carried out on a larger scale.

SUMMARY

Quick chemical tests for measuring available plant nutrients in the soil that may serve as a basis for a fertilizer recommendation have only a limited value for cover crop fertilization in orchards.

Greenhouse trials, on small soil samples, are more valuable than chemical tests. The greenhouse trials require 6 to 10 weeks and give rather definite information as to soil deficiencies for any particular plant.

The sunflower has proved to be a good indicator plant for greenhouse studies. In field trials, orchard cover crops are affected by deficiencies of those elements found to be most deficient by greenhouse methods using the sunflower as an indicator.

Miniature field plots have been very helpful in quickly obtaining data which may tentatively serve as a basis for a fertilizer recommendation.

No type of study which fails to give adequate consideration to the physical properties of the soil can be considered a proper basis for orchard soil management practices.

The tentative conclusion to date is that orchard soils should be first subjected to physical and chemical studies, particularly relating to the depth, capillary porosity, and noncapillary porosity, and to the aeration throughout a 10-foot profile.

The physical and chemical studies should be accompanied by greenhouse trials to establish major and minor soil deficiencies. These should be followed by long-time trials in the field where the cumulative effect of the use of various fertilizers over a period of years may be established.

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EFFECT OF CERTAIN ORCHARD PRACTICES ON THE POTASSIUM STATUS OF A NEW YORK FRUIT SOIL

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The investigations of Wander and Gourley (14) on mulch plots maintained for the last 20 to 30 years, indicate that the practice of applying a straw mulch to orchard soils for many years is associated with markedly greater exchangeable potassium content of Wooster silt loam when compared to a cultivation-cover crop system of soil management, or when compared to bluegrass areas in the middles between mulched trees. Quick test determinations of potash availability in orchard fertilizer plots on a similar soil suggest that commercial potash salts are not always as effective as mulch treatments in increasing the exchangeable potassium level of the soil below a depth of 6 inches.

The study herein reported was undertaken to examine further the effect of mulch on the exchangeable potassium content of a New York orchard soil in the Dunkirk series and to determine whether such effect could be obtained in a reasonably short time. Another objective of the investigation was to study the effect of farm manure on the potash status of an orchard soil.

PLOT TREATMENTS

Orchard A

Orchard A consists of mature bearing trees planted approximately 40 feet by 40 feet in the Cornell University orchard at Ithaca, N. Y. Rows A[1] and B[1] of this block consist of 27-year-old McIntosh apple trees on an imperfectly drained phase of Dunkirk silty clay loam, the surface layer of which contains about 30 per cent of clay. Over a period of years the records show that these two rows of trees have yielded only about two-thirds as much fruit as another block of comparable trees in an adjoining part of the orchard on a better drained phase of the same type of soil (8).

Trees of row A[1] received an application of strawy farm manure at the rate of ½ ton per tree from 1924 to 1929 inclusive, and at the rate of 1 ton per tree from 1930 to 1939 inclusive. The manure was applied during the spring in the circular area under, and somewhat beyond, the spread of the branches. Row B[1] has been in sod continuously with the exception of 1932 and 1933, when straw mulch was applied.

Row E has been heavily mulched with hay or straw 5 out of the 10 years previous to the time the soil samples were obtained. In addition, it received spring fertilizer treatments as follows: 1937—30 pounds of KNO_3 per tree; 1938—25 pounds of KCl plus 20 pounds of $(NH_4)_2SO_4$ per tree.

Row F received 15 to 20 pounds of ammonium sulfate per tree during the 5 years previous to sampling, but never any potassium salts. It has been in sod continuously with the exception of the 1935 season, when it received a heavy straw mulch. All the soil samples from this orchard were taken in the summer of 1938.

Orchard 31

Orchard 31, a block of young bearing trees in another part of the Cornell University orchard at Ithaca, N. Y., is on a soil similar to that of Orchard A, but possibly not quite so uniformly poorly drained. Three cultural systems are compared in this block: cultivation, sod, and heavy straw mulch. Each plot consists of a single row of about ten trees planted 40 feet apart. The plots are separated by buffer rows and are in duplicate. The cultivation plots are cultivated only once each year in the spring, but in this particular situation this suffices to inhibit weed growth for most of the summer, and that which does develop in late summer is sparse. The mulch plots receive an 8–10-inch layer of cereal straw (largely wheat and oats) applied uniformly over a strip 40 feet wide extending 20 feet on each side of the tree row. It is estimated that this material is applied at the rate of at least 15 to 20 tons per acre. Nitrogen in the form of $Ca(CN)_2$ has been applied at the rate of 7 pounds to a tree. The soil samples from this block were obtained in August, 1938, at which time the treatments had been in progress for 4 years. Previously, the entire block had been in sod.

Orchard 43

Orchard 43, a block of young bearing apple trees also in the University orchard at Ithaca, N. Y., received various cultural and fertilizer treatments. The soil is somewhat variable, and is similar to that of Orchard 31. Before the 1936 season, all the rows concerned in this study received standard nitrogen fertilization. Since then, the fertilizer treatments per tree have been as follows:

YEAR	N-TREATED ROWS (NOS. 3, 11, 19, 27, 35, 43)	NK-TREATED ROWS (NOS. 7, 15, 23, 31, 39, 47)
1936	5 pounds $NaNO_3$	6 pounds KNO_3
1937	3 pounds $Ca(CN)_2$	4 pounds KNO_3
1938	15 pounds $NaNO_3$	15 pounds KNO_3
1939	10 pounds $NaNO_3$	10 pounds $NaNO_3$ plus 10 pounds KCl

These treatments were all made in early spring and were spread uniformly over the area occupied by the tree. In this orchard, both soil and foliage samples were obtained in August, 1939.

All soil samples for analysis were composites of four to ten borings each. The borings were made in a semicircular band just under the spread of the branches of the trees.   In Orchard 31 thirteen sets of replicate samples were made for each of the three treatments.   A set consisted of soil samples of five empirical depths: 0–3, 3–6, 6–12, 12–24, and 24–36 inches.   In Orchard A, eight sets of replicate samples were taken from rows A^1 and B^1, but only two replicates were made in rows E and F.   In Orchard 43, only one set of samples was obtained from each of the four rows concerned in the study.

Exchangeable potassium was determined by weighing 15-gm. samples of air-dry soil passing a 1-mm. sieve into 30-ml. Gooch crucibles fitted with filter paper discs and leaching with 350 ml. of 1 N neutral ammonium acetate solution.   The leaching apparatus was similar to that described by Wander and Gourley (14).   The leaching process usually required 24 to 36 hours for these silty clay loam soils.   The leachate was analyzed for potassium by the method of Hibbard and Stout (2) after the evaporated residue, transferred to 50-ml. porcelain crucibles, was treated with a mixture of dilute H_2SO_4 and HNO_3 and evaporated until fuming ceased, then ignited for several hours at 450–500°C. in a muffle furnace.   Numerous replicate analyses made on certain soil samples indicated that the probable error of a single determination was of the order of 2 per cent.

The leaf-sampling technique used was similar to that described in previous papers (9, 10).   The foliage samples for potassium analyses were ashed for about 18 to 22 hours in a muffle furnace set to attain a maximum temperature of about 480°C. in 6 to 8 hours.   Potassium was estimated by the method of Hibbard and Stout (2) on these samples also.

EXPERIMENTAL RESULTS

Exchangeable potassium

The data summarized in table 1 show that 4 years of heavy mulch treatment in Orchard 31 very markedly increased the amount of exchangeable potassium in the first 24 inches of the soil as compared to sod and cultivation treatments.   Below 24 inches no significant effect of mulch is apparent.   Table 2 indicates the effect of the various soil management practices on the volume weight of the soil.   When the exchangeable potassium data are calculated to a soil volume basis, it will be noted that there is an apparent increase of more than 400 pounds per acre in the top 6 inches of soil under the mulch.   If the soil below the first 6 inches is assumed to have a volume weight of 2×10^6 pounds per acre-6-inches, then there appears to be a net increase of more than 600 pounds of exchangeable potassium per acre in the first 24 inches of soil associated with the mulch treatment.

 Estimates were made of the rate of application of mulch materials by weighing the straw on several replicate areas 1 foot square in orchard 31.   From the data thus obtained, it was calculated that the mulch was applied yearly

at a rate of 15 to 20 tons per acre. From data found in the literature (5) it may be conservatively estimated that the mulch material contained a minimum of 0.75 per cent of potassium on an air-dry basis. If one assumes also the minimum calculated rate of application of 15 tons per acre yearly, then at least 225 pounds of potassium per acre was supplied each year by the mulch. This would amount to a total of 675 pounds in the three seasons previous to

TABLE 1

Effect of various soil management practices on the exchangeable potassium content of the soil in Orchard 31

TREATMENTS	MEAN EXCHANGEABLE POTASSIUM CONTENT OF AIR-DRY SOIL AT VARIOUS DEPTHS				
	0–3 inches	3–6 inches	6–12 inches	12–24 inches	24–36 inches
	p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*
Cultivation	159.0	99.4	88.7	108.3	79.6
Sod	175.5	98.7	87.9	101.6	75.0
Straw mulch	457.1	308.7	165.8	141.8	88.9
Odds (for *F* value) that variance among treatments is significant*	>99:1	>99:1	>99:1	>99:1	<19:1
Least difference* required for significance between means by odds of 99:1	88.4	27.5	41.2	23.5	44.2

* These values were obtained by statistical treatment of the data by the analysis of variance method as described by Love (4, chap. XIII).

TABLE 2

Effect of various soil management practices on the volume weight of the soil in Orchard 31 and on the exchangeable potassium expressed on a volume basis

TREATMENTS	MEAN WEIGHT OF 702.3 cc. OF AIR-DRY SOIL*	CALCULATED WEIGHT OF TOP ACRE—6 INCHES OF AIR-DRY SOIL	MEAN EXCHANGEABLE POTASSIUM IN TOP 6 INCHES OF SOIL	MEAN EXCHANGEABLE POTASSIUM IN TOP ACRE—6 INCHES
	gm.	*pounds*	*p.p.m.*	*pounds*
Cultivation	923.6	1,788,000	129.2	231
Sod	841.5	1,629,000	137.1	223
Mulch	876.9	1,698,000	387.9	659

* The least difference for significance between these means is 29.3 gm. for odds of 19:1, or 40.6 gm. for odds of 99:1. The *F* value for effect of treatments indicates significance by odds of more than 99:1.

sampling, or a total of 900 pounds per acre in the 4-year period (including the year that the samples were obtained) since these plots were established. Undoubtedly, a part of the potassium contained in the application of mulch made in the spring of 1938 was released to the soil before August, 1938, when the samples were taken. It would seem, therefore, that the potassium contained in the mulch itself would be ample to account for the increase in exchangeable potassium observed.

Similar effects on the exchangeable potassium status of soil may be produced by heavy manure applications. The data summarized in table 3 indicate that over a period of years farm manure has produced an increase of approximately 2000 pounds per acre in the first 24 inches of soil. Again by reference to Lyon and Bizzell (5), it may be seen that the potassium content of manure on a fresh-weight basis is a minimum of 0.3 per cent. It may be conservatively estimated that the 1-ton applications of manure were spread uniformly over a circular area 36 feet in diameter, or at a rate of about 40 tons per acre. On .he basis of these calculations potassium would be supplied in the manure at the rate of about 240 pounds per acre per year. Thus the manure applied in the last 10 years alone would account for the increase observed under manure, provided fairly efficient adsorption by the soil colloids is assumed. Similar

TABLE 3

Effect of farm manure on the exchangeable potassium content of the soil in Orchard A, rows A¹ and B¹

TREATMENTS	MEAN EXCHANGEABLE POTASSIUM CONTENT OF AIR-DRY SOIL AT VARIOUS DEPTHS				
	0–3 inches	3–6 inches	6–12 inches	12–24 inches	24–36 inches
	p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*
Farm manure mulch, row A¹..............	1,118	790	468	184	80
Middles (sod) rows A¹ and B¹.............	357	213	159	110	80
Sod (+ Mulch*) row B¹.................	195	141	111	94	54
Odds (for *F* value) that variance among treatments is significant†...............	>99:1	>99:1	>99:1	99:1	<19:1
Least difference required for significance between means by odds of {19:1........	115	91	55	56	34
{99:1........	160	126	76	77	48

* Row B¹ received applications of straw mulch in 1932 and 1933. Previous to, and since that time, the row has been in sod.

† These values were obtained by statistical treatment of the data by the analysis of variance method as described by Love (4).

effects of manure on orchard soils have been noted by Wallace and Proebsting (13).

Table 4 presents data which indicate the effect of irregular mulch treatment combined with heavy applications of potash salts. Since samples from these treatments were replicated only once, these data should be interpreted on a qualitative basis only. The rate of application of potassium per acre in the drip region of the tree from which the samples were obtained may be estimated by assuming that the fertilizer was spread evenly in a circular band 6 feet wide, having an inside diameter of 24 feet and an outside diameter of 36 feet. On this basis it can be calculated that potassium was applied at the rate of approximately 750 pounds per acre (see treatments for Orchard A) in the form of commercial fertilizer salts. If it is estimated that 2 tons of mulch was also

applied in this same area during the 10 years before the samples were obtained, then at least 2000 pounds of potassium per acre was applied in this manner

TABLE 4

Effect of certain treatments on the exchangeable potassium content of the soil in Orchard A, rows E and F

SAMPLE LOCATION	TREATMENT*	EXCHANGEABLE POTASSIUM CONTENT OF AIR-DRY SOIL AT VARIOUS DEPTHS			
		0–3 inches	3–6 inches	6–12 inches	12–24 inches
		p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*
Tree E-5	Straw mulch irregularly plus K salts	830	563	351	137
Middle E-5 & F-5	Sod	287	145	92	87
Tree F-5	Sod (except 1935)—no K salts	356	294	209	124
Tree E-7	Same as E-5	710	467	220	96
Middle E-7 & F-7	Sod	290	157	104	76
Tree F-7	Same as F-5	322	297	261	94

* See text for details.

TABLE 5

Effect of potash fertilization on the exchangeable potassium and certain other chemical characteristics of the soil in Orchard 43

ROW NUMBER	TREATMENT*	0–6-INCH LAYER					6–12-INCH LAYER					12–24-INCH LAYER
		pH	Exchange K†	Exchange capacity‡	Base saturation	K saturation	pH	Exchange K†	Exchange capacity‡	Base saturation	K saturation	Exchange K†
			p.p.m.	*m.e.*	*per cent*	*per cent*		*p.p.m.*	*m.e.*	*per cent*	*per cent*	*p.p.m.*
23	Cultivation + cover crop + NK	5.2	670	12.6	58.1	13.7	5.1	221	11.4	63.1	5.0	91
19	Cultivation + cover crop + N	5.8	86	13.7	70.4	1.6	6.0	94	12.4	77.6	1.9	61
39	Sod + NK	4.9	885	14.0	50.3	16.3	5.1	268	13.7	50.1	4.8	69
35	Sod + N	6.2	71	14.4	68.8	1.3	6.2	43	10.7	70.5	1.0	48

* See text for details.
† In air-dry soil.
‡ Per 100 gm. air-dry soil.

to the drip region of the tree. Thus it appears that ample potassium was supplied to account for the increase indicated.

That the exchangeable potassium content of Dunkirk silt loam in the Cornell

experimental orchard may be markedly increased by heavy applications of potash salts alone is indicated by the analyses of samples from Orchard 43 presented in table 5. The potash-treated rows are indicated to have from 1500 to 2000 pounds per acre of potassium in exchangeable form in the top 24 inches of soil, assuming an acre-foot of air-dry soil to weigh 4×10^6 pounds. More than 90 per cent of this is found in the top 12 inches.

The potash salts were applied uniformly over the area occupied by the tree in the orchard: 100 square feet in 1936 and 1937, 400 square feet in 1938 and 1939. On this basis a total of about 2200 pounds of potassium per acre of surface has been applied to the treated rows.

The limited data presented in table 6 indicate that most of the added potassium (whether from fertilizer salts or mulch) which has been adsorbed by

TABLE 6

A comparison of exchangeable and Neubauer* values for available potassium on a few soil samples obtained from the Cornell experimental orchard

SOIL NUMBER	SOIL LAYER	SOURCE	TREATMENT	EXCHANGEABLE K†	NEUBAUER VALUES, K
	inches			*p.p.m.*	*p.p.m.*
231	3–6	Orchard 31	Cultivation	89	151
236	3–6	Orchard 31	Sod	123	146
241	3–6	Orchard 31	Mulch	360	485
261	3–6	Orchard 31	Cultivation	132	140
266	3–6	Orchard 31	Sod	73	109
271	3–6	Orchard 31	Mulch	310	241
600	0–6	Orchard 43	Heavy K fertilization	670	760
603	0–6	Orchard 43	No K fertilization	86	230
606	0–6	Orchard 43	Heavy K fertilization	885	646
609	0–6	Orchard 43	No K fertilization	71	98

* A biological method for determining potash availability involving the use of rye seedlings (6, 7).

† In air-dry soil passing a 1-mm. sieve.

the exchange complex is available to rye seedlings. These data also suggest that this soil contains some potassium in nonexchangeable form which is available to plants.

Exchange capacity and base saturation

Analyses were made of the 3–6-inch samples from Orchard 31 to determine the effect of the treatments on the exchange capacity and base saturation of the soil. These data are summarized in table 7. It will be noted that the mulch treatment appears to have increased the exchange capacity of the soil slightly when compared to sod or cultivation treatments. The degree of base saturation under sod appears significantly lower than under mulch, but no significant difference between mulch and cultivation is indicated.

TABLE 7
Effect of various soil management practices on the exchange capacity and the degree of base saturation of the 3–6-inch layer of soil in Orchard 31

TREATMENT	MEAN[*] EXCHANGE CAPACITY	MEAN[*] BASE SATURATION	MEAN[*] K SATURATION
	m.e./100 gm.	per cent	per cent
Cultivation............................	13.70	54.6	1.9
Sod...................................	13.84	45.4	1.8
Mulch................................	16.37	59.0	4.8
Odds (for *F* value) that variance among treatments is significant...............	>19:1 < 99:1	>19:1 < 99:1	...
Least difference for significance between means by odds of { 19:1...............	1.95	10.4	...
99:1...............	2.64	14.0	...

[*] Mean of 13 replicate samples.

TABLE 8
Effect of farm manure on the potassium content of shoot leaves of apple trees in Orchard A[*]

Date collected	Source	Treatment	K IN DRY MATTER	WEIGHT OF 100 LEAVES	K PER LEAF	ASH IN DRY MATTER	K IN ASH
			per cent	decigm.	mgm.	per cent	per cent
August 24, 1938	Row A¹, Tree 7	Heavy farm manure	1.39	390	5.4	7.65	18.2
	B¹—7	Sod	1.05	384	4.0	7.13	14.7
	A¹—1	Heavy farm manure	1.39	419	5.8	6.48	21.5
	B¹—1	Sod	0.99	405	4.0	6.95	14.2
August 29, 1939	A¹†	Heavy farm manure	1.49	474	7.1	6.71	22.2
	B²†	Sod	1.06	499	5.3	6.96	15.2

[*] All the analytical data presented in this table are averages of duplicate samples which agree closely.

† These samples were obtained by compositing 10 leaves from each of 10 trees in each row. In 1938 the duplicate samples of 100 leaves each were obtained from individual trees.

TABLE 9
Effect of potash fertilization on the potassium content of the foliage of apple trees in Orchard 43

TREATMENT	VARIETY	NUMBER OF TREES[*]	K CONTENT OF LEAVES		SIZE OF LEAVES		MEAN K PER LEAF
			Mean per cent in dry matter	Odds†	Weight of 100 leaves	Odds†	
					decigm.		mgm.
Nitrogen + potash	McIntosh {	12	1.32	99:1	458	15:1	6.1
Nitrogen alone		9	0.99		426		4.2
Nitrogen + potash	Cortland {	12	1.33	>99:1	453	>99:1	6.0
Nitrogen alone		10	0.64		395		2.5

[*] A sample of 100 shoot leaves from each tree was obtained August 24, 1939 in all cases.

† Odds that the difference between the means is significant. These odds were calculated by means of Fisher's method for determining the significance of the difference between means

Potassium content of apple foliage from various plots

The potassium content of the apple leaves from trees growing in some of the plots concerned in this study reflects the exchangeable potash level of the soil. The data presented in table 8 indicate that in both the 1938 and 1939 seasons the manure-treated row of Orchard A had a greater potash content of the leaves than did the sod row. The marked influence of potassium fertilization in Orchard 43 on the potassium content of the foliage is shown by the data presented in table 9. The level of exchangeable and Neubauer potassium in the untreated rows of Orchard 43 appears to be somewhat lower than elsewhere in the Cornell experimental orchard. The leaf weight data presented in table 9 suggest that potash fertilization has stimulated the vigor of some trees. Observations indicate, however, that waterlogging of the soil is the factor limiting the vigor of many trees in this variable soil situation.

DISCUSSION

This study is primarily concerned with the effects of certain orchard soil management practices on the exchangeable potassium content of the soil. This is a chemical characteristic of the colloidal fraction of the soil, and though there is evidence to suggest that it is an important basis of the potassium-supplying power of the soil, it is recognized that many other soil factors of equal or greater importance may condition the ability of plant roots to accumulate potassium from the soil. The studies of Hoagland and Martin (3), Wallace and Proebsting (13), Schachtschabel (11), Bray and DeTurk (1), and others all indicate that the exchangeable potassium above a certain level (which is characteristic of a given soil) is largely available to plants. Furthermore, these studies also indicate that many soils have reserves of nonexchangeable potassium which are directly or indirectly available to plants.

It would seem justifiable to conclude from the data previously considered that the mulch treatment in Orchard 31 and the manure treatment in Orchard A have both greatly increased the supply of potassium available to the trees on these soils. At the present time there is no apparent difference in the size or vigor of the trees associated with these high-potassium soils. Thus it appears that potassium availability is not the limiting factor for tree vigor in these two orchards. The nature of the soil profile is such that drainage is imperfect, and thus waterlogging of the soil, with the associated restricted rooting and inadequate oxygen availability, seems likely to be the limiting factor to growth and productivity over a period of years (8). Whether or not response to the mulch or manure treatment would be obtained independently of moisture factors, if the drainage of the soil were better, is an open question. The performance of trees elsewhere in the orchard located on a better drained phase of the same soil type, and having about the same level of exchangeable potassium as do the sod plots of Orchards 31 and A, suggests that the potassium-supplying power of this soil is adequate for a high level of vigor and

productivity. Orchard 43, on the other hand, may have a somewhat inadequate supply of available potassium, but here the data are limited, and again drainage overshadows other factors in parts of the orchard.

. The cause of the increase in exchangeable potassium induced by heavy mulch or manure treatments seems quite apparent from the data presented and the calculations made. The obvious and simple explanation is that the increase associated with these treatments is merely due to an increase in potash saturation of the soil colloids which resulted from the leaching of potassium compounds out of the decomposing mulch or manure materials into the soil. No doubt large amounts of carbohydrate and other food materials would also be released to the soil and would greatly stimulate microbiological activity. It might be postulated that conditions associated with this increased level of biological activity are responsible for the increase in exchangeable potassium noted. The studies of Vandecaveye (12) indicate that incubation of soil with a source of carbohydrate material has little or no effect on the exchangeable potash level of the soil.

The available evidence on the composition of materials such as cereal straw and hay which are suitable for use as mulch in orchard practices, together with the studies of Wander and Gourley (14) and those herein considered, serve to emphasize the fact that, from the point of view of mineral nutrition, these materials are, in effect at least, organic potash carriers. The fact that 100 pounds of mulch material is likely to contain $\frac{3}{4}$ to 2 pounds of potassium or the equivalent of $1\frac{1}{2}$ to 4 pounds of the ordinary commercial chemical carriers probably should receive more emphasis in the evaluation of this common practice in fruit growing. Nor should the possibility be neglected that other minerals of significance may be contained in mulch materials. For example, a few preliminary analyses of some of the samples from Orchard 31 suggest that the mulch-treated soil contains considerably more water-soluble boron than the sod-treated soils.

Wander and Gourley (14) feel that their studies indicate that mulch is more effective in increasing the level of exchangeable potassium in the subsoil than is fertilization with potash salts. If this were definitely established, it might be a point strongly in favor of the use of mulch for supplementing the supply of potassium available to orchards on deficient soils. Unfortunately, in the studies herein considered, the plans of the plots are such that it is difficult to draw any definite conclusions in this regard.

In order to clarify the action of mulch materials on the potash status of soil as compared to supplements of mineral salts of potassium, it would be desirable to set up a system of plots in several carefully selected soils of known constitution which would enable accurate comparison of the effects on both soil and plant factors of equal amounts of potassium in the form of mulch and mineral salts. Furthermore, it would be enlightening to study the nature of the potash compounds released by mulch and the rate of such release during the course of one season.

SUMMARY

Data are presented which indicate that the practice of treating orchard soils with liberal amounts of straw mulch or farm manure markedly increases the exchangeable potassium content of such soils. This is in agreement with investigations previously reported by other workers.

The use of heavy straw mulch in orchards appears to increase slightly the exchange capacity and base saturation of the soil as compared to sod or cultivation methods of orchard soil management.

In the few instances studied, the exchangeable potassium level of the soil was reflected by the potash content of foliage of the orchard trees associated with it.

It is suggested that these studies emphasize that the high potassium content of mulch materials should be given more attention in the evaluation of the effects of mulching as an agricultural practice.

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A DOUBLE CENTRIFUGE TUBE FOR THE SEPARATION OF SOIL MINERALS BY MEANS OF HEAVY LIQUIDS[1]

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During the course of several years' work in the separation of soil minerals, by means of heavy liquids, into groups according to their specific gravities for subsequent petrographic and chemical study, a double centrifuge tube assemblage has been devised which appears to meet the requirements both for completeness of separation and for ease of manipulation. It is the purpose of this paper to describe this equipment and also to give examples of results obtained in the separation of some mineral groups in the very fine sand separates of several soils.

The parts of the double centrifuge tube assemblage are shown in plate 1, figure 1. It will be seen that the assemblage consists of two parts, an outer tube A constructed of heavy pyrex glass having walls 2 mm. thick and a flattened base reenforced with heavy glass, and an inner tube B drawn out to form a bulb at the lower end. The purpose of the bulb is to provide a trap for any mineral fragments which might be carried below the first opening by convection currents during introduction of the sample and evacuation previous to centrifuging. This inner tube is provided with a heavy rubber collar which rests on the top of the outer tube during operation. It was found by experience that, for satisfactory operation, the taper of the drawn parts of the inner tube should be about 20° and the outlet in the end should have a diameter of about 1 mm. The rubber stopper is used in removing the tube with the light fraction after separation, as will be described later. The approximate dimensions of the tube may be judged from the scale. The tubes can be constructed so as to be accommodated by any size centrifuge cups; hence, actual dimensions are not important here.

A separation is carried out as follows: The weighed outer tube A is filled to the mark with heavy liquid. The inner tube B is inserted, and a 0.2–0.5-gm. sample is weighed directly into it. Fragments which may adhere to the walls of the inner tube above the surface of the heavy liquid are carefully washed down with a small quantity of heavy liquid introduced by means of a pipette with a very fine opening. The tubes containing the sample are placed in a vacuum jar, and the whole is evacuated to remove occluded air from the mixture of heavy liquid and minerals. After evacuation, the minerals are again

stirred by washing about 1–2 ml. of heavy liquid carefully down the walls of the inner tube. The tube and contents are then centrifuged for 15 minutes at about 900 r.p.m., and the contents are stirred as described above. The centrifuging and stirring are repeated, and the tube and contents are finally centrifuged at 1400 r.p.m. for 30 minutes. The stopper C is next inserted into the inner tube, the end of the glass tube is closed with the finger as shown in plate 1, figure 2, and the inner tube containing the light minerals is lifted out. The contents are transferred to a weighed Gooch crucible with a sintered bottom, washed with acetone, dried at 70° C., and weighed.

TABLE 1

Separations according to specific gravities of mineral groups from very fine sands*

SOILS FROM WHICH VERY FINE SANDS WERE DERIVED	MINERALS HEAVIER THAN SPECIFIC GRAVITY 2.95		MINERALS LIGHTER THAN SPECIFIC GRAVITY 2.65		
	a	b	a	b	c
	per cent	*per cent*	*per cent*	*per cent*	*per cent*
Gilpin, Pennsylvania................	1.70	1.65	9.50	9.80	
Volusia, Pennsylvania..............	1.00	0.95	11.10	10.90	
Dunmore, Virginia.................	0.95	0.80	18.32	18.83	
Hagerstown, Indiana...............	1.70	1.75	20.78	20.72	
Hagerstown, Pennsylvania..........	0.40	0.45	40.19	40.45	40.40

* a and b and a, b, and c are replicates.

TABLE 2

Minerals identified in the two mineral groups of table 1

HEAVY GROUP		LIGHT GROUP
Zircon	Sillimanite	Orthoclose
Tourmaline	Augite	Microcline
Hornblende, green	Diopside	Albite
Rutile	Kyanite	Diatoms
Anatase	Epidote	Undecomposed
Chlorite	Monazite	plant residues
Barite	Fluorite	
Garnet	Corundum	

The liquid in tube A is decanted off, and the heavy separate at the bottom is washed with acetone and dried at 70°C. The tube and contents are weighed by means of a counterpoise. To ensure accurate weights, it is necessary to allow these tubes to cool for 1 hour after removal from the oven, then to wipe them carefully with cheesecloth, and allow them to stand 30 minutes before weighing.

In the separation of minerals having specific gravities rather close together, such as quartz and microcline, difficulty was experienced in introducing the sample into the inner tube by the means described. The quartz had a tendency to settle during evacuation and carry some feldspar fragments with it. This

was overcome by placing the sample and heavy liquid in a beaker for evacuation then stirring the mixture carefully and drawing a sample into the inner tube in the same manner as in filling a pipette.

For this purpose a piece of rubber tubing with a screw clamp is attached to the glass tubing of stopper C. If the screw clamp is closed after the sample has been drawn in, the mixture of heavy liquid and sand remains in the tube. This sample should fill the bulb about two-thirds full. The outer part of the inner tube is then wiped off, and about the same volume of heavy liquid as that containing the sample is taken up by the means used in removing the sample from the beaker. The inner tube is placed into the outer tube which contains the main supply of heavy liquid, the vacuum is released, and the sample is carried to the top by the two liquids seeking a balance. In drawing the sample into the inner tube, care must, of course, be exercised so that the height of liquid in the inner tube will be below that in the outer one. In calculating the results, the total sample of sand is the sum of the two separates determined.

In all cases, microscopic check of all fractions of sands is necessary to determine whether the separations are complete.

The heavy liquids used for this work were mixtures of S-tetrabromethane and nitrobenzene made up to the desired specific gravities as described by Volk.[2]

Table 1 sets forth the results of separations of mineral groups according to their specific gravities. These determinations were carried out on the very fine sand separates (particles 0.1 to 0.05 mm. diameter) of the various soils. The soils had been cleaned of free iron oxide by the nascent hydrogen sulfide method of Truog[3] or the nascent hydrogen method of the author.[4] Both methods give clean soil separates, ideal for mineralogical study.

The determinations given in table 1 are in satisfactory agreement. Microscopic examination showed that the separations were clean-cut.

Table 2 lists the various minerals found in the two groups.

SUMMARY

A double centrifuge tube consisting of an inner and an outer tube for the quantitative separation of mineral groups has been described. The manipulations necessary to make typical heavy liquid separations of sands are given in detail.

Some results obtained on the very fine sand fraction (particles 0.10–0.05 mm. diameter) of some soils, and a list of the minerals identified in the different specific gravity groups are given.

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PLATE 1

Fig. 1. Parts of the modified centrifuge tube and a tube assembled for use. Approximate dimensions of tube may be judged from 6-inch ruler at left.
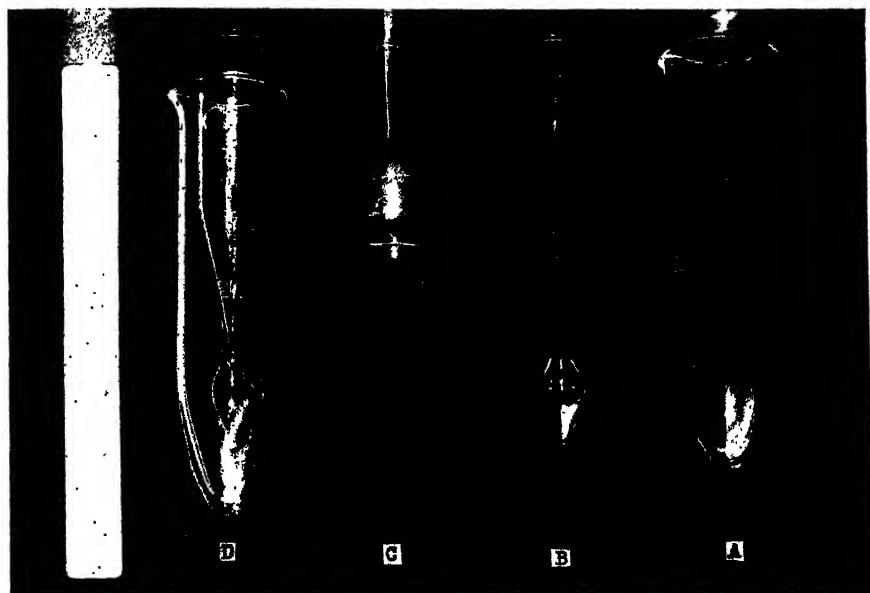Fig. 2. Manner of removing light mineral group after separation.

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Fig. 1

Fig. 2

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SOIL STUDIES WITH RADIOACTIVE PHOSPHORUS: SIGNIFICANCE OF BIOLOGICAL MEASUREMENTS OF THE RETENTION OF APPLIED PHOSPHORUS BY SOILS[1]

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Studies on the retention or fixation of soluble phosphates by soils have, for the most part, been confined to the mechanism of the reactions and to the substances involved. From a consideration of the work reported by Davis (2), Dean (3, 4), Ford (5), Metzger (6), Murphy (7), Ravikovitch (8), Scarseth (9), and many others, it is apparent that the retention of phosphates by soils entails both a surface adsorption and chemical precipitations, and that many substances may be involved. The relative importance, however, of these two types of phenomena in relation to the ability of plants to utilize fixed phosphorus, is not fully understood.

The writers (1) have pointed out that it is possible, without interference from the native soil phosphorus, to trace the amount and rate of entry into plants of radioactive phosphorus applied to a soil. Hence it should be possible to obtain biological measurements of the degree of retention of applied phosphorus by soils. It was the purpose of this investigation to consider the significance of such measurements.

RELATIVE ABSORPTION BY TOMATO SEEDLINGS OF RADIOACTIVE PHOSPHORUS APPLIED TO SOIL AND SAND CULTURES

Radioactive phosphorus was added to various soil and sand cultures, in order to determine the rate of absorption by tomato seedlings of phosphorus from these media. The soil samples included 12 types common to the Hawaiian Islands and also Superior clay loam from Wisconsin. The salient features of these soils are listed in table 1.

The soil cultures were prepared by thoroughly mixing 10 ml. of an adequate nutrient solution and 10 ml. of a stock solution of radioactive phosphorus[3]

[3] Radioactive phosphorus is prepared as follows: Red phosphorus is bombarded by deuterons in the cyclotron, thereby converting about one atom per billion (10^9) to the radioactive isotope; the red phosphorus is then converted to Na_2HPO_4. Thus, the concentration

with 350 gm. of soil and transferring to a small pot. One tomato seedling, about 6 inches tall, was then transplanted into each pot. Comparative measures of the rate of absorption of the radioactive phosphorus by the seedlings were made at 2-day intervals from the time of transplanting. For this purpose the potted plants were so placed under a Lauritsen electroscope that the terminal bud and the first new leaves were just below the electroscope window. A sheet of lead placed over the pot shielded the electroscope from soil radioactivity (plate 1). The radioactivity values were obtained by timing the discharge rate of the electroscope and then correcting for the decay of the radioactive phosphorus[4]. The corrected values plotted against time are shown in figure 1,

TABLE 1

Description of soils used in radioactive phosphorus studies

SYMBOL	ORIGIN OF SAMPLES	VEGETATION	pH
a	Kalaheo, Kauai, Hawaiian Islands	Pineapples	4.6
b	Hanapepe, Kauai, Hawaiian Islands	Pineapples	5.7
c	Hanapepe, Kauai, Hawaiian Islands	Pineapples	5.8
d	Koloa, Kauai, Hawaiian Islands	Pineapples	4.5
e	Helemanu, Oahu, Hawaiian Islands	Pineapples	4.5
f	Kunia, Oahu, Hawaiian Islands	Pineapples	4.4
g	Waipio, Oahu, Hawaiian Islands	Pineapples	4.7
h	Kona, Hawaii, Hawaiian Islands	Coffee	5.6
i	Waimea, Hawaii, Hawaiian Islands	Truck farm	6.2
j	Kailua, Oahu, Hawaiian Islands	Papaya	6.1
k	Ewa, Oahu, Hawaiian Islands	Truck farm	8.0
l	Manoa, Oahu, Hawaiian Islands	Bananas	5.4
m	Superior clay loam; Ashland, Wisconsin		4.7

and give a comparison of the rate of absorption of radioactive phosphorus by tomato plants grown in the various soils. For the first 10 days, the values plotted are averages of measurements on three plants, and for the remaining

of the radioactive isotope is very small. Upon the ejection of an electron, an atom of radioactive phosphorus becomes a stable, nonradioactive sulfur atom.

The stock solution of radioactive phosphorus used in these experiments was of such concentration that the 10-ml. portions added in the culture series contained approximately 20 mgm. disodium phosphate. Since each soil pot contained 350 gm. soil, this treatment was equivalent to adding 25 pounds per acre of phosphorus.

[4] The law for radioactive decay is:

$$I = I_0 e^{-\lambda t},$$

where I_0 is the intensity (or radioactivity) at some arbitrary "zero time" such as the time of the start of the experiment, I is the intensity after time t, e is the base of natural logarithms, and λ is the radioactive decay constant of the particular radioactive element under consideration. λ is related to the half-life (the time for the radioactivity to drop to one-half its original value) by:

$$\lambda = \frac{0.693}{\text{half-life}}$$

time, for only two plants.   In all instances the replicates for each soil were in agreement.   Figure 1 shows that there were marked differences in the rates of uptake of radioactive phosphorus by the plants growing in the various soils. Apparently the plants growing in soils j, k, i, m, b, and c removed phosphorus more readily than did those growing in the other soils.

The rate of absorption of phosphorus from sand cultures was measured to furnish a comparison of the absorption from soils with that from a more ideal
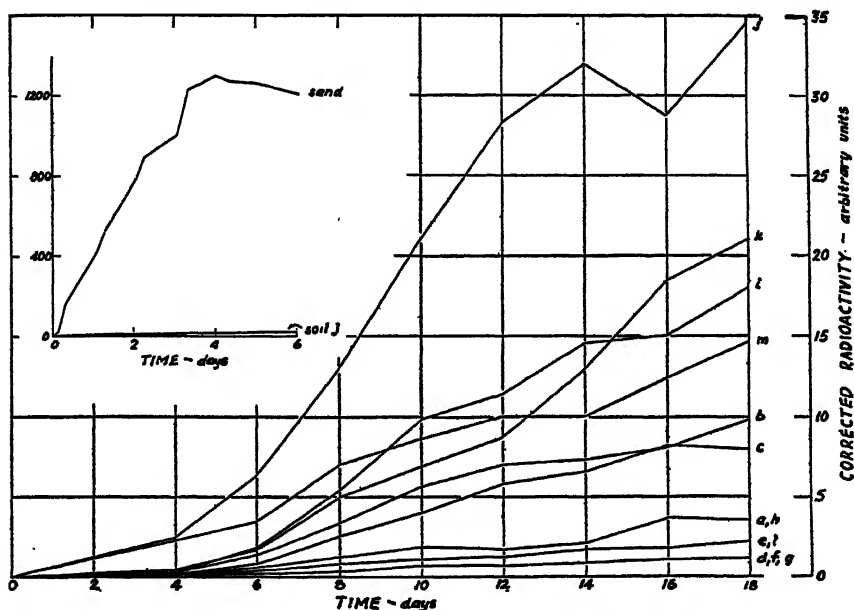

FIG. 1. ABSORPTION OF RADIOACTIVE PHOSPHORUS BY TOMATO SEEDLINGS GROWN IN 13 SOILS.   INSERT: ABSORPTION FROM SOIL j COMPARED TO ABSORPTION FROM SAND CULTURE

medium.   Tomato seedlings from the same batch as the foregoing were transplanted into containers holding 900 gm. of silica sand, and a nutrient solution was circulated through the sand several times a day.   The plants in the sand

The half-life of radio-phosphorus has been determined to be 14.3 days.   Using this value, the law of radioactive decay becomes

$$I = I_0 e^{-0.0485t},$$

where t is expressed in days.   This may be rewritten as

$$I_0 = I e^{0.0485t},$$

where the exponential factor is the correction factor by which any radioactivity is multiplied in order to correct it back to the beginning of the experiment (zero time).

The actual mathematical manipulation of obtaining "corrected radioactivities" involves determining the appropriate time, t, for each correction, looking up the value of e^x corresponding to that value of x ($= 0.0485t$), and multiplying the measured radioactivity by this value.

cultures were allowed to establish themselves for 6 days, after which 10 ml. of the radio-phosphorus stock solution was added.

The rate of absorption of radioactive phosphorus from the sand cultures is shown in the insert of figure 1. The rate of absorption of radioactive phosphorus from the soil showing the greatest release is also represented, for the period from 6 to 12 days after transplanting. Presumably the much slower absorption from the soil than from the sand cultures is a result of the two factors: (a) the retention or fixation of the radioactive phosphorus by the soil, and (b) the incomplete distribution of the roots throughout the soil. In this study it was not possible to distinguish between these two factors.

TOTAL ABSORPTION BY TOMATO SEEDLINGS OF RADIOACTIVE PHOSPHORUS APPLIED TO SOIL AND SAND CULTURES

A more accurate measurement of the absorption of radioactive phosphorus from the soil and sand cultures was obtained by determining the radioactivity of the plant ashes. Though the results for the growing plants were only semi-quantitative, the error in the ash activities shown in tables 2 and 3 usually did not exceed 5 per cent. In each instance the dried plant material was treated with a standard amount of an alcoholic magnesium nitrate solution and burned until a white ash was obtained. The radioactive strength of these ashes was measured by the method previously described (1), all ash measurements being corrected for radioactive decay since the start of the experiment. In order that all measured activities might be expressed relative to the total amount of radioactive phosphorus used, a 10-ml. aliquot of the original stock solution was evaporated to dryness, ashed with magnesium nitrate, and its activity measured under conditions identical with those for the plant ashes. A value of 10,000 arbitrary units of radioactivity was assigned to this measure, and, by means of appropriate factors, all the ash values were put on a comparative basis. Thus, a corrected plant ash value of 1,000 arbitrary units would indicate that one-tenth of the phosphorus originally added was present in the ash examined.

The total absorptions of radioactive phosphorus by the tomato plants grown in the sand cultures and in the soil allowing the greatest uptake are compared in table 2. Over 60 per cent of the radioactive phosphorus applied to the sand cultures was absorbed in 6 days, whereas from the soil less than 1 per cent was absorbed in 10 days and almost 3 per cent in 19 days.[5] Again it was not possible to decide whether the comparatively extremely low absorption from the soil was caused by fixation or by the inadequate distribution of roots throughout the soil mass. The marked increase, however, in the amount of radioactive phosphorus present in the plants after 19 days' growth as compared with that after 10 days suggests the possible importance of root distribution. There was little indication of the movement of radioactive phosphorus within the soil mass.

[5] A tomato seedling grown in an aerated water culture under comparable conditions absorbed 73 per cent of the added radioactive phosphorus in 5 days.

A comparison of the radioactive strengths of the ashes of the plants grown on the various soils is given in table 3. Two series of plants were harvested—

TABLE 2

Comparison of the absorption by tomato seedlings of radioactive phosphorus added to sand and soil cultures

CULTURE	PLANT PART	RADIOACTIVITY ARBITRARY UNITS	RECOVERY	DRY WEIGHT
			per cent	*gm.*
Sand culture 1	Tops	4400	44.0	1.61
	Roots	1800	18.0	0.52
	Total	6200	62.0	2.13
Sand culture 2	Tops	4400	44.0	1.69
	Roots	1850	18.5	0.52
	Total	6250	62.5	2.21
Soil j 10 days' growth	Tops	79	0.79	1.11
Soil j 19 days' growth	Tops	237	2.37	3.42
	Roots	38	0.38	0.45
	Total	275	2.75	3.87

TABLE 3

Radioactivity of the ashes and dry weights of tomato seedlings grown in various soils to which 10,000 arbitrary units of radioactive phosphorus was applied

SOIL	FIRST HARVEST 10 DAYS' GROWTH Tops only		SECOND HARVEST 19 DAYS' GROWTH Tops only		Roots only		Tops plus roots	
	Dry weight	Radio-activity arbitrary units	Dry weight	Radio-activity arbitrary units	Dry weight	Radio-activity arbitrary units	Dry weight	Radio-activity arbitrary units
	gm.		*gm.*		*gm.*		*gm.*	
j	1.11	79.	3.42	237.	0.45	38.	3.87	275.
k	0.71	17.	2.12	85.	0.41	30.	2.53	115.
i	0.68	26.	2.30	71.	0.48	20.	2.78	91.
m	....	....	1.14	42.	0.14	7.8	1.28	50.
b	1.07	14.	2.23	29.	0.50	20.	2.73	49.
c	0.77	9.3	1.94	27.	0.41	16.	2.35	43.
a	0.67	5.6	1.45	12.	0.40	21.	1.85	33.
h	0.68	6.1	1.78	11.	0.36	11.	2.14	22.
l	0.68	3.2	1.48	9.7	0.40	11.	1.88	21.
e	0.59	3.2	0.90	4.5	0.23	3.6	1.13	8.1
g	0.76	2.4	0.98	2.9	0.22	4.2	1.20	7.1
f	0.67	1.9	1.07	2.4	0.23	1.9	1.30	4.3
d	0.69	0.8	0.71	1.6	0.23	1.6	0.94	3.2

one after 10 days of growth and the other after 19 days. Preliminary experiments had shown that the growth of tomatoes in the various soils could not be

kept equal for more than about 10 days. Consequently a series was harvested after 10 days to minimize the influence of unequal growth on the absorption of radioactive phosphorus from the various soils. The dry weights and the radioactivity values of the plants which were harvested after 10 days' growth are given in table 3. These data show a range of 0.8 to 79 in radioactivity of the ashes of the plants grown in the different soils, whereas the range in the dry weights was 0.59 to 1.11 gm. Since the range in dry weight is small compared with that in radioactivity values, the effect of differences in growth of the plants in the various soils was considered unimportant in comparison with the differences in the phosphorus-fixing power of the soils. Results for the harvest after 19 days' growth show much the same relationships as for the earlier harvest. In this instance, however, there is an apparent relationship between the dry weights of the tops and the radioactivity of the ashes.

The relative order of magnitude of the ash radioactivity of plants grown in the various soils was the same for the two harvests. Also, this order was the same as that for the curves of figure 1. The roots of the tomato seedlings grown for the 19-day period were also studied; the range in the dry weights and also in the ash radioactivity was considerably less. The values paralleled in order those for the tops, except for the Wisconsin soil, in which root growth was very poor. The total radioactivity of the roots and tops shows that 2.75 per cent of the total phosphorus applied to the best soil had been removed by the plants, while from the poorest soil only 0.03 per cent was removed.

COMPARISON OF THE ABSORPTION BY TOMATO AND BY SUDAN GRASS SEEDLINGS OF RADIOACTIVE PHOSPHORUS FROM SOILS

An indication of the effect of plant species on availability of phosphorus applied to soils was obtained by comparing the uptake of radioactive phosphorus from the same soils by tomato and by Sudan grass seedlings.

After the tomatoes discussed in the foregoing sections were harvested, the soil was removed, mixed, and placed again in the pots. Four Sudan grass seedlings were then transplanted into each pot and allowed to grow for 40 days, after which the plants were harvested and the radioactivity of the ashes was determined.

Figure 2 shows the relative absorption of radioactive phosphorus by the tomato seedlings harvested at 19 days compared to Sudan grass seedlings grown for 40 days. The values for the plants grown on soils e, g, f, and d were too low to be represented on the scale chosen. These data show that certain of the soils were able to supply phosphorus readily to Sudan grass but not to tomato seedlings. Thus, in considering the availability of phosphorus in different soils, the plant being grown is an important factor. A second series of pot tests gave a similar comparison.

An alternative method of illustrating the effect of the plant upon the availability of the radioactive phosphorus applied to the different soils is given in table 4. Here the soils are grouped into three classes—low, medium, and high —in respect to their fixation capacity as judged from experiments with tomato

and Sudan grass seedlings. This classification shows that four soils, i, m, h, and l, were judged to have a lower fixing capacity when Sudan grass was the indicator, and two soils, b and c, appeared to have a higher fixation capacity for Sudan grass.
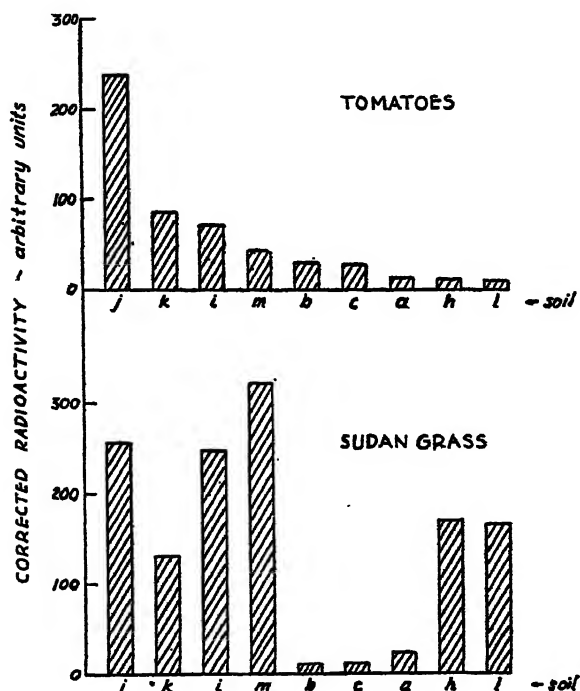

FIG. 2. COMPARISON OF AMOUNTS OF RADIOACTIVE PHOSPHORUS ABSORBED BY TOMATOES AND BY SUDAN GRASS FROM THE SAME SOILS

TABLE 4

Comparative phosphorus fixation of soils as estimated from the absorption of radioactive phosphorus by tomato and Sudan grass seedlings

	COMPARATIVE PHOSPHATE FIXATION OF SOILS		
	Low	Medium	High
Tomatoes..................	j	k, i, m, b, c	a, h, l, e, g, f, d
Sudan grass................	m, j, i	k, h, l	b, c, a, e, g, f, d

COMPARISON OF PHOSPHORUS-FIXING CAPACITY OF SOILS AS MEASURED BY CHEMICAL AND BIOLOGICAL METHODS

The foregoing growth experiments with radioactive phosphorus gave relative biological measures of the power of the various soils to fix applied phosphorus. It should be valuable to interpolate these data and compare them with the usual laboratory measurements of the phosphorus fixation of soils. The

phosphorus fixation capacities of the various soils, evaluated both by chemical and by biological methods, are given in table 5. These data are best interpreted after a consideration of the various methods of determination and calculation, which were as follows:

Extraction with acid after addition of phosphorus

One-half gram of soil, 500 p.p.m. of phosphorus as KH_2PO_4, and 45 ml. of water were placed in a flask and evaporated to dryness at 80°C. The contents of the flask were then shaken with 200 ml. of 0.002 N H_2SO_4 at pH 3 (10), and the phosphorus in the filtrate was determined. To account for the acid-soluble

TABLE 5

Percentage phosphorus fixation of soils as estimated chemically by laboratory studies and biologically by the absorption of radioactive phosphorus from soils by plants

SOIL	PERCENTAGE PHOSPHORUS FIXATION DETERMINED BY			
	Extraction with 0.002 N H_2SO_4	Equilibrium system with water	Estimated from absorption of radioactive phosphorus by tomato seedlings	Estimated from absorption of radioactive phosphorus by Sudan grass
j	20	0	0	0
k	43	51	58	49
i	58	54	67	4
m	31	26	82	−12
b	85	80	82	96
c	84	73	84	96
a	88	85	88	91
h	90	94	92	34
l	91	99	92	36
e	76	96	97	99
g	87	99	97	99
f	75	99	99	98
d	91	99	98	99

phosphorus originally in the soil, 50 ml. of water containing 0.5 gm. soil was evaporated to dryness and extracted as above. The phosphate fixation percentage was calculated as follows:

$$\text{Per cent fixation} = \frac{(500 + \text{phosphorus in soil originally}) - \text{phosphorus extracted after application}}{500 + \text{phosphorus in soil originally}} \times 100$$

Equilibrium system with water

One-half gram of soil, 500 p.p.m. of phosphorus as KH_2PO_4, and 95 ml. of water were placed in a flask and shaken mechanically for 1 hour. The flask was allowed to stand overnight, the contents were filtered, and the phosphorus

in the filtrate was determined. The phosphorus fixation percentage was calculated as follows:

$$\text{Per cent fixation} = \frac{500 - \text{phosphorus in filtrate}}{500} \times 100$$

A variation of this method, in which radioactive phosphorus was added and determinations were made with the electroscope, has been outlined previously (1). The results obtained by this method showed very little correlation with any of the other series of fixation values of table 5. It is thought that this discrepancy was caused by colloidal particles which, having sorbed radioactive phosphorus, did not settle out of solution. Thus, the measured radioactivity was higher for soils which were more readily dispersed under the existing experimental conditions.

Uptake of radioactive phosphorus by plants

Evaluation of the phosphorus-fixing capacity from the data available in table 3 is only possible if certain assumptions are made. Thus, since both of the chemical methods showed soil j to have the lowest phosphorus-fixing capacity (see table 5), the incomplete uptake of the radioactive phosphorus by the plants growing in this soil was assumed to be caused, for the most part, by an inadequate root distribution throughout the soil mass. Consequently the percentage fixation was calculated by arbitrarily assigning the fixation capacity of soil j at zero and using the ratio of the radioactive strength of ashes of the plant grown on the other soil to that of soil j. For example, the radioactive strength of the ashes of the plants grown on soils j and k were 275 and 115, respectively (see table 3), and the percentage phosphorus fixation of soil k was calculated to be $100 - \dfrac{115}{275} \times 100$, or 58 per cent.

Turning again to the data presented in table 5, we see that the agreement between the two chemical methods was somewhat inconsistent. Lower results, however, were obtained by the acid extraction method for the high fixing soils. The agreement between the phosphorus fixation as determined by the water equilibrium system method and by the absorption of radioactive phosphorus by tomato plants grown for 19 days is surprisingly close, the only outstanding exception being for soil m, where the very poor root growth of the tomato seedlings may have been a complicating factor. There was poor agreement between chemical and biological methods when Sudan grass was used as the indicator plant. These results apparently imply that Sudan grass is able to utilize the so-called fixed phosphorus present in some soils, whereas the tomatoes did not utilize this fixed phosphorus so readily.

SUMMARY

This paper on soil studies with radioactive phosphorus gives consideration to, first, the rate and total absorption by plants of radioactive phosphorus

added to soil and sand cultures, and, second, a comparison and evaluation of the phosphorus-fixing capacity of soils by chemical and biological methods. The results may be summarized as follows:

The rate and the total absorption by plants of radioactive phosphorus added to soils vary with the soil and the species of plant grown.

The rate and the total absorption by plants of radioactive phosphorus added to sand cultures were much greater than from the soil cultures. Apparently this difference can be attributed both to phosphorus fixation by the soils and to inadequate root distribution.

The percentages of phosphorus fixation shown by the various soils, calculated from the observed absorption of radioactive phosphorus by tomato plants, paralleled closely the values obtained from chemical laboratory studies on the sorption from soil-water systems.

Apparently tomato seedlings are unable to utilize readily the so-called fixed phosphorus of soils, whereas Sudan grass utilizes some of the fixed phosphorus present in certain soils.

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PLATE 1

MEASURING THE RADIOACTIVITY OF A GROWING TOMATO SEEDLING WITH A LAURITSEN ELECTROSCOPE
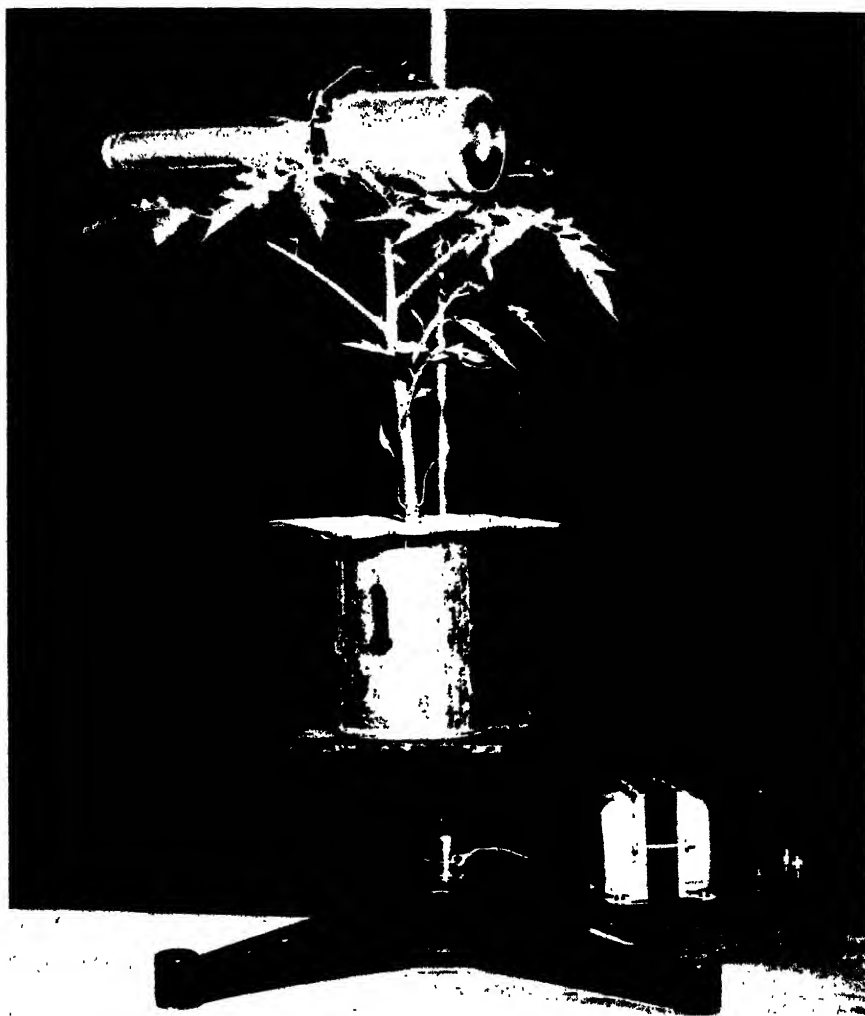
DETERMINATION OF NITRATE-NITROGEN WITH A PHOTOELECTRIC COLORIMETER

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During the course of soil nitrate determinations and nitrification studies using the phenoldisulfonic acid method and visual comparative apparatus, a need was felt for a more rapid, sensitive, and accurate technic. When a large number of soil samples or bacterial cultures were analyzed, considerable time was lost in clarifying certain extracts and in removing extraneous yellow or brown colors present in many of the soil solutions. Where nitrates were extremely low in amount, it was necessary either to report nitrate concentration as a "trace" or to repeat the procedure, concentrating relatively large amounts of the extract. A further objection to employment of the visual comparative method lay in the fact that eye fatigue and other subjective factors associated with making a large series of measurements probably contributed to inaccuracies of the determination.

The Evelyn photoelectric colorimeter[2] was found to be well suited to at least a partial solution of the problems involved. Through employment of this apparatus, it was possible to eliminate the use of standard nitrate solutions for comparative purposes, after preparation of a calibrated curve giving percentage transmission of roughly monochromatic light through solutions of known concentration of nitrate-phenoldisulfonic acid compound. The effects of turbidity and extraneous colors were eliminated by the employment of a blank in the initial adjustment of the apparatus. Very pale colors, difficult or impossible to read with the visual colorimeter, were easily determined with the photoelectric colorimeter. After a short "warming up" period of the instrument, readings could be made without difficulty at the rate of 5 to 7 samples a minute (10 to 14 tubes). Percentage transmission of the standard solutions being known, nitrate concentration of unknown samples could be measured from the calibrated curve to the fourth or fifth decimal place.

EXPERIMENTAL

A stock standard nitrate solution was prepared in the usual manner by dissolving 0.607 gm. pure sodium nitrate in 1 liter of redistilled nitrate-free water.

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[1] The author is now stationed at Rocky Mountain Laboratory, Hamilton, Montana.

[2] Evelyn, K. A. 1936 A stabilized photoelectric colorimeter with light filters. *Jour. Biol. Chem.* 115: 63–75.

A 50-ml. portion of this solution was evaporated to dryness over a water bath, the cooled residue dissolved in 2 ml. phenoldisulfonic acid reagent, and the solution diluted to 500 ml. One milliliter of this standard solution contains 0.01 mgm. nitrogen as nitrate. Sufficient ammonium hydroxide solution (diluted 1:1) was added to measured volumes of the standard solution to bring out the yellow color of the reaction compound, and the volume was made up to exactly 50 ml.

A spectrophotometric analysis was made of the colored solution to determine the spectral region in which selective absorption occurred in greatest extent.
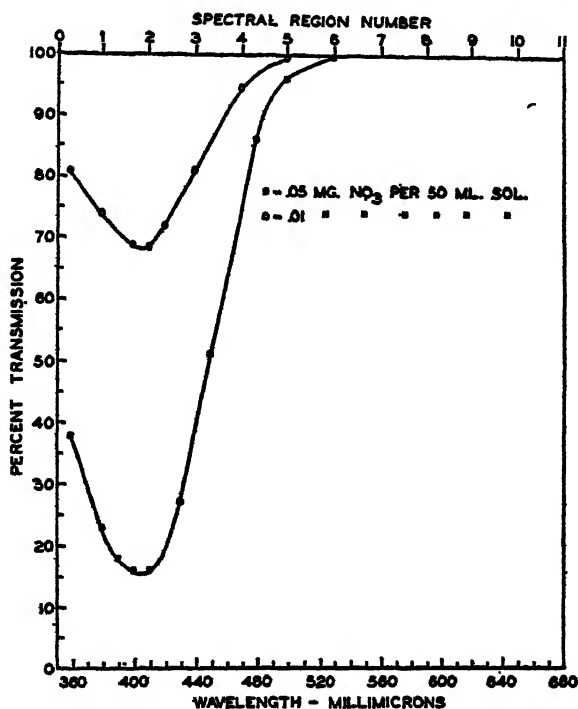

FIG. 1. PERCENTAGE TRANSMISSION OF STANDARD NITRATE SOLUTIONS

The data obtained with a Coleman spectrophotometer show maximum light absorption at wavelengths between 400 and 410 mμ, with a relatively sharp increase in percentage transmission at either end of this zone (fig. 1).

When percentage transmission of light of wavelengths 400 and 420 mμ, respectively, was observed for solutions containing varying concentrations of nitrate, a logarithmic relationship was noted (fig. 2). A constant may be obtained by employing the formula $C = \dfrac{L}{K}$, where C = concentration of nitrates in milligrams per 50 ml. solution, and L = log 100 − log per cent transmission. Calibration constants obtained in this manner are listed in table 1.

Filter No. 400, prepared by the Rubicon Company for the Evelyn apparatus, has specified transmission limits of 380 to 430 mμ, and filter No. 420 transmits light of from 380 to 460 mμ wavelength, with transmission maxima at 400 and 420 mμ, respectively. From table 1 it is evident that within the range of
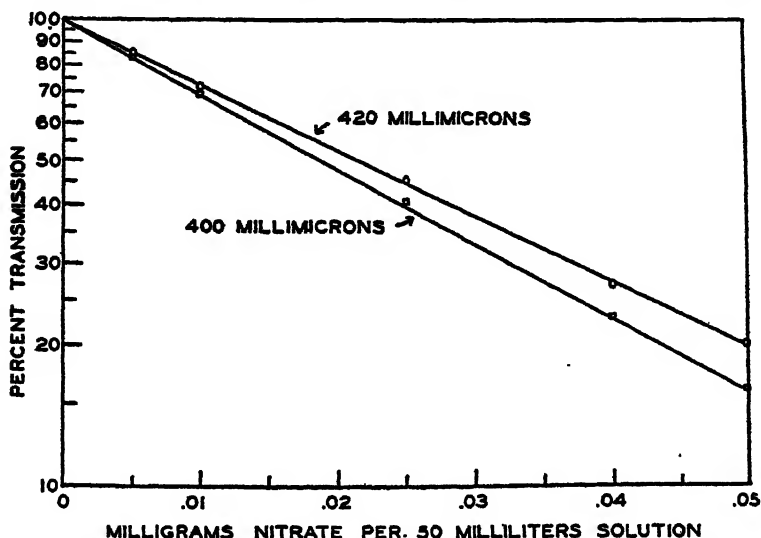

FIG. 2. PERCENTAGE TRANSMISSION OF STANDARD NITRATE SOLUTIONS AT 400 AND 420 mμ WAVELENGTHS

TABLE 1

Calibration constants for solutions of different nitrate concentrations

C	PERCENTAGE TRANS-MISSION AT 400 mμ WAVELENGTH	K_{400}	PERCENTAGE TRANS-MISSION AT 420 mμ WAVELENGTH	K_{420}
.005	83.00	16.18	85.00	14.12
.010	69.00	16.12	72.00	14.27
.015	57.75	15.89	61.75	13.95
.020	48.00	15.95	52.50	13.99
.025	40.00	15.92	45.00	13.88
.030	33.50	15.83	38.00	14.00
.040	23.00	15.95	27.00	14.23
.050	16.00	15.92	20.00	13.98
Average......................		15.97 ± .2		14.05 ± .2

concentrations employed, from 2 to 5 per cent more light of 400 than of 420 mμ wavelength was absorbed by the colored solution. In practice, however, it was found that filter No. 420, which is supplied regularly with the apparatus, was sufficiently selective. With a nitrate concentration of only 1 p.p.m., more than 70 per cent of the light of this spectral band was absorbed, whereas almost

90 per cent was absorbed at a concentration of 2 p.p.m. Filter No. 420, therefore, was employed in all determinations.

For standardization and for each test, two solutions were prepared, a blank and a sample solution, respectively. Both solutions contained the same volume of standard nitrate solution, but the blank was diluted immediately to 50 ml. with nitrate-free water and the sample solution contained in addition sufficient ammonium hydroxide solution to bring out the yellow color of the reaction compound. It was necessary to employ a blank for each different sample solution, since some color was present in the standard acid nitrate solution alone. Sample solutions and corresponding blanks containing from 0.005 to 0.1 mgm. nitrate per 50 ml. solution were thus prepared.

These solutions were then transferred to carefully selected absorption cells, a blank placed in the apparatus with filter No. 420 in position, and the intensity

TABLE 2

Average percentages transmission of solutions of different nitrate concentrations, filter No. 420, and corresponding calibration constants

C	PERCENTAGE TRANSMISSION FILTER NO. 420	K
.005	87.00	12.10
.010	76.00	11.92
.015	66.50	11.80
.020	58.25	11.74
.025	51.75	11.45
.030	46.00	11.23
.040	36.00	11.10
.050	28.50	10.90
.060	23.00	10.63
.070	18.00	10.47
.080	15.00	10.30
.090	12.25	10.13
.100	10.25	9.89

of the light beam adjusted so that a full-scale deflection of 100 divisions was obtained on the galvanometer. Without alteration of the light intensity, the blank was replaced by the corresponding sample solution, and the new galvanometer deflection was read directly in percentage transmission of the solution. These determinations were repeated several times with three different lots of reagents. Readings obtained with the different lots varied only slightly. The average results are shown in table 2. Values for K were calculated from the formula $C = \dfrac{L}{K}$. A calibration curve was prepared by plotting percentage transmission as the ordinate and nitrate concentration as the abscissa (fig. 3).

Examination of the data in table 2 shows that, in this case, the value for K (calibration constant) decreases more or less regularly from 12.10 to 9.89 as nitrate concentration increases. For this reason it does not appear possible

to use a calibration constant for calculation of nitrate concentration by the method employed. It is probable that by substituting a somewhat more highly selective filter, such as No. 400, a useable calibration constant might be derived, since it is evident from figure 1 that the color of the reaction compound is changing its transmission more rapidly at a wavelength of 420 mμ than at 400. This, of course, would also tend to restrict to some extent the total range of measurable nitrate concentration unless smaller aliquots of samples in which nitrates might be expected in greater amounts were selected.

The failure of K to remain uniform when filter No. 420 is employed is of no practical importance, however, since the calibrated curve can be made with
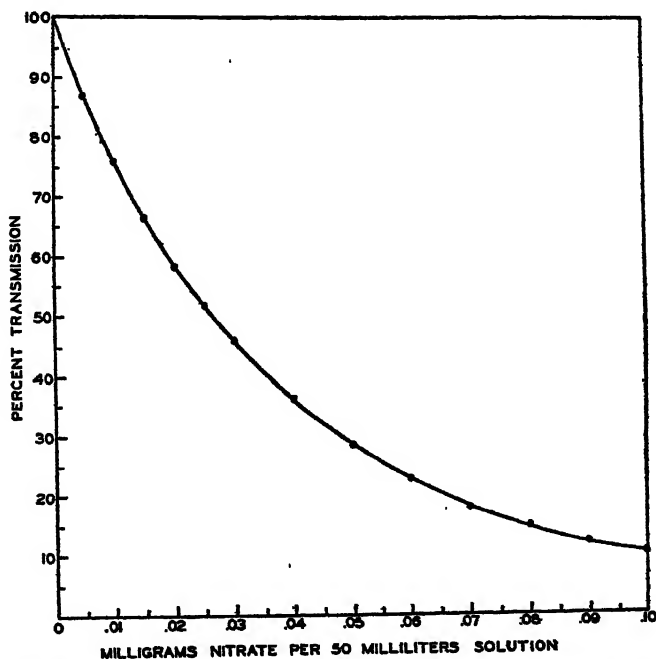

FIG. 3. PERCENTAGE TRANSMISSION OF STANDARD NITRATE SOLUTIONS, FILTER No. 420

ease and is more readily employed than a calibration constant where large numbers of samples are to be measured.

In order to check the reliability, for use with soil extracts, of the calibrated curve prepared from the observed transmission of standard nitrate solutions, a number of determinations were carried out.

Extracts were prepared from air-dried soils passed through a 1-mm. mesh sieve. To each 50-gm. sample of soil was added 65 ml. of saturated calcium sulfate solution and 185 ml. nitrate-free distilled water. The soil-water mixture was rotated in a mixing device for 5 minutes at 32 revolutions per minute. The mixture was then passed twice through filter paper, no other precautions

being taken to remove colloidal turbidities and no attempt being made to remove extraneous colors, as by treatment with hydrogen peroxide.

A number of aliquots (25 ml.) of the filtered extract were removed, a pinch of calcium carbonate was added to each (since the soil samples were acid in reaction), and the solutions were partly evaporated over an electric plate, the desiccation being completed over a water bath to avoid charring. Each portion was then treated with 2 ml. phenoldisulfonic acid reagent and diluted to approximately 25 ml. with distilled water. Duplicate samples in each group were selected for direct nitrate determinations, ammonium hydroxide solution

TABLE 3

Nitrates in soil samples as determined by the photoelectric colorimeter

SOIL SAMPLE	NO₃ ADDED	TRANSMISSION	NO₃ PER 50 ML. SOLUTION	AVERAGE NO₃ OBSERVED	AVERAGE NO₃ THEORETICAL
	mgm.	*per cent*	*mgm.*	*p.p.m.*	*p.p.m.*
FS 10-7	0	61.00	.0182		
10-7	0	58.75	.0197	3.80	.....
10-7	.01	46.25	.0297		
10-7	.01	47.50	.0285	5.82	5.80
10-7	.03	31.50	.0457		
10-7	.03	29.75	.0482	9.40	9.80
10-7	.05	19.50	.0675		
10-7	.05	21.00	.0640	13.16	13.80
FS 10-8	0	65.50	.0156		
10-8	0	66.50	.0151	3.08	.....
10-8	.02	42.50	.0332		
10-8	.02	42.00	.0337	6.70	7.08
10-8	.04	25.00	.0560		
10-8	.04	25.00	.0560	11.20	11.08

being added and each diluted to exactly 50 ml. Blanks were prepared in the usual manner for each sample solution.

To remaining duplicate sample portions and blanks were added known amounts of nitrogen as nitrate, and percentage transmission was again observed. Data from a typical trial are recorded in table 3. It is evident from these results that deviation from the expected values was no greater than variation between duplicate samples.

SUMMARY AND CONCLUSIONS

The Evelyn photoelectric colorimeter has been employed for quantitative determination of nitrates in soil samples and in culture media.

The use of this apparatus enables rapid and accurate measurement of nitrate content by the phenoldisulfonic acid method even in the presence of extraneous colors, semiturbid solutions, and minimal amounts of nitrates. Standard nitrate solutions may be dispensed with after preliminary calibration of the instrument.

Lack of uniformity of K (calibration constant) when filter No. 420 is employed is not an obstacle to the method reported, in view of the ease of preparation of a calibration curve and the stability of the calibration once made, as well as the rapidity with which nitrate concentration can be read from the curve.

MORPHOLOGICAL CLASSIFICATION OF SOIL STRUCTURE

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GENERAL DEFINITION

The term "soil structure" denotes an arrangement of the soil material into aggregates in which the primary particles of such a material are held together by ties stronger than the ties between the adjacent aggregates.

The aggregates range in size from microscopically small to several inches in diameter, and differ from one another in shape, in stability, and in degree or distinctness of separation of each from its neighbors.

On the basis of the size of the aggregates, one may distinguish macrostructure from microstructure. Roughly, the dividing line between the two is at the limit of plain visibility of the aggregates by the naked eye, or at a diameter of about 1 mm. This boundary is arbitrary but is recognized for convenience of study.

Structure is one of the principal characteristics by which the types and "species" of soil are identified. Since, for the most part, identification must be made in the field without the aid of a microscope, only the relatively large units of macrostructure are considered here. Investigations of microstructure require special laboratory equipment and are beyond the technical limit of morphological studies in the field.

Structure characterizes a condition of the soil material intermediate between a loose or "single grain" condition, which represents a complete description of the ties between the primary particles of such a material, and a massive condition, representing a uniform cohesion of the primary particles throughout the soil. Aggregates are not formed in either of these conditions; thus, such materials are regarded as structureless. These structureless conditions represent the two opposite extremes, approaches to which indicate the vanishing of the structure. A loose or single grain and a massive condition of soil material may be regarded as physical parameters of the soil structure.

The mechanism by which soil structure develops is not precisely known. Presumably, soil material can become aggregated in two general ways and, perhaps, two kinds of genetically different soil structure can be formed: a soil structure can develop because of a gradual breaking down of a massive soil material due to its shrinkage and cracking on drying; or it may develop because of aggregation or sticking together of the primary particles beginning from a coagulation of the soil colloids. Perhaps, the formation of micro-

structure depends chiefly upon the second or synthetic process, whereas the development of macrostructure is due to a process of breaking down or fragmentation. Indeed, this should not infer that the synthetic process ends at the upper limit of the microaggregation or that the reverse process ceases to operate at the lower limit of the macrostructure. In some instances the breaking down of the coherent soil proceeds as far as the complete pulverization of the material or far below the lower limit of the macrostructure, whereas, in other instances, the reverse process may extend up to the binding of the whole bulk of soil into one solid mass.

Structure is not a static property of the soil material but changes with changes in moisture content. In part, the effect of water on the soil structure indicates the reversibility of cementation of the aggregates. Perhaps such a reversibility is an outstanding characteristic of the dynamic soil structure. A permanent irreversible cementation (or petrification) of the soil material, as in certain hardpans or concretions, does not produce true structure. The concretions are not structural aggregates. They are the products of the segregation of compounds like iron oxide, manganese, lime, or gypsum, representing a local static petrification of the soil mass.

Since the kind or "species" of soil macrostructure is determined by the general shape of the aggregates, their average size, and the grade of distinctness of the aggregation, the morphological classification of these species must take into account these three aspects of soil structure. Accordingly the proposed system of classification of soil structure includes the recognition of types, classes, and grades of structure.

Classification of soil structure, like that of any other natural objects, consists of the grouping of related individuals or species into various units of a series of consecutive categories. The prerequisite of a satisfactory classification is a clear definition of each composite unit and each category and of the principles of their grouping.

Whenever one attempts to classify the links of a continuous series of things or facts without any clear lines of demarcation between the individual links, one must first solve the problem of whether to recognize only a few distinct but rather inclusive units, each characterized by a rather wide range of variability in its determining characteristics, or many closely defined units characterized by a narrow range of variability in their features. Perhaps the proper solution of such a problem depends upon how much one knows about the object of classification. Sufficient data may justify a recognition of many fine distinctions, whereas meagerness of data may force one to prefer a reasonable generalization and consequently a recognition of fewer and broader units.

Moreover, any breaking down of a continuous series of things or facts into a number of individual units is always somewhat arbitrary. The boundaries between such units are arbitrary rather than natural. Every arbitrary boundary represents a certain zone of confusion. One of the objects in every system of classification is to reduce this zone of confusion to a minimum. Frequently

this can be accomplished by the elimination of as many nonessential, arbitrary separations as possible.

Our present knowledge of soil structure—its origin, stability, and significance in relationship to the other characteristics of the soil—is rather limited. The variations in shape, size, and stability of the aggregates present a continuous series in each of these aspects. No system of classification, therefore, can claim any finality at this time, and the one here proposed should be regarded merely as an attempt to formulate certain principles for further systematic investigations of soil structure. The results of such new investigations may be expected, in turn, to lead to improvements in classification.

TYPES OF SOIL STRUCTURE

The type of soil structure is determined by the general shape of the aggregates. As a unit of classification, each type of structure represents a group of many individual forms or species characterized by a similar general shape of the aggregates. Four different types of soil structure are recognized and defined as follows:

The first type includes the various forms of horizontal or *platy* structure. All these forms are characterized by aggregates of which the horizontal axes, extending parallel to the surface of the soil, are longer than the vertical, or those perpendicular to the surface. The aggregates of such structure are in the shape of plates, leaflets, or minute lenses (pl. 1, fig. 1). Very few are sufficiently firm to be separated one by one without destruction. The ratio of their horizontal axes to the vertical ones ranges from about 3 to 1 to more than 10 to 1, and their vertical axes, which represent the thickness of the plates, range from less than 1 to more than 10 mm. in length. The structure of this type develops usually in the A and particularly in the A_2 horizons of various leached, podzolized, and degraded soils.

The second type includes the various forms of vertical or *prismatic* structure, which is characterized by aggregates the horizontal axes of which are shorter than the vertical. The aggregates have the shapes of irregular prisms, small pillars, or simply vertically elongated irregular lumps (pl. 1, fig. 2). In many instances, they are sufficiently firm to be separated without much difficulty and handled roughly without destruction. The ratio of their vertical axis to the horizontal one ranges from about 2 to 1 to 5 to 1, and their horizontal axes, representing the diameter or thickness of the prisms, range from less than 1 to more than 10 cm. This type of structure develops in the heavy B horizons of various soils (pl. 1, fig. 3), especially of those in semiarid regions, like the chestnut.

The individual species of the structure of this type differ from each other in the general character of prisms (square, pentagonal, hexagonal, etc.), in the sharpness of their edges, in the shape of the tops of prisms (flat or rounded), in the ratio of vertical axes to the horizontal ones (short and long prisms), and in various other respects. In many instances the long and relatively thin

prisms break horizontally on drying into the coarse plates or blocks (pl. 1, fig. 4).

The third type includes the forms of *blocky* (lumpy or fragmental) structure, which is characterized by aggregates having horizontal and vertical axes more or less equal in length to each other. The aggregates are in the shape of irregular blocks or lumps, usually with rather sharp edges and more or less smooth facets representing a mirror image of the surface of the adjacent aggregates (pl. 2, fig. 1). Usually they are firm, are easily separated from one another, and can be freely handled without damage. They range in size from about 1 mm. to more than 5 cm. Structure of this type is common in the horizons of a great variety of soils. It is particularly conspicuous in the heavy B horizons of podzols and many other podzolic soils, as well as some soils of the semiarid and arid regions (pl. 2, fig. 2).

The individual species of structure of this type differ from one another in the average size of the aggregates, in their durability, in the general character of their facets, and in the distinctness and sharpness of their edges, as well as in other respects.

The fourth type includes the various forms of *granular* structure, which is characterized by more or less rounded aggregates (pl. 2, fig. 3). The roundness of the aggregates is very arbitrary, indeed. Perhaps, distinctly rounded structural aggregates are not formed in any soil. A careful examination of samples of the best developed granular, "nutlike," and similar structural aggregates demonstrates that the great majority of the aggregates are very irregular and rather angular in shape. Some of them may be relatively more rounded than others, but well-rounded ones are rather exceptional and, indeed, do not characterize the structure as a whole. Therefore, the roundness of the aggregates refers to the absence of distinct smooth facets and edges more than to the spheroidal shapes. Usually the surface of such aggregates is rather rough (pl. 2, fig. 4).

These aggregates range in diameter from less than 1 mm. to more than 1 cm. Usually they are fairly stable and lie in the soil loosely; not only is there little difficulty in separating them from one another, but indeed it is difficult to handle a sample of dry soil having such a structure without its falling apart. Most commonly structure of this type characterizes the A horizons of soils rich in humus, such as chernozems, brown forest, and the A_1 horizon of many podzolic soils.

The structure of the fourth type does not differ from that of the third type in relative length of axes of the aggregates. Therefore it could be regarded not as an independent type of structure but as a variety or subtype of the third type. The principal difference between the third and fourth types is in the geometrical forms of the aggregates, which are determined by the character of their surface. The full significance of such a difference becomes clear when one considers the general layout of the soil material and the qualitative aspect of its porosity. The aggregates of the third type lie rather close to-

gether, and their swelling when wet may close completely the voids between them. The aggregates of the fourth type lie more loosely, leaving much larger and more irregular voids between the adjacent lumps. These voids may be filled with water but never close because of swelling of the aggregates.

Morphological analyses of the structure of many different soils demonstrates a gradual transition from the structure of the third type to that of the fourth type. Similarly, there is no sharp line of demarcation between the structures of the third and second types. In some soils the ratio of the vertical axes to the horizontal ones is about 1 to 1; in other soils it is $1\frac{1}{2}$ to 1, 2 to 1, 3 to 1, and so on. Perhaps there is no sharp demarcation between any pair of types of soil structure. Each of the four types described above is best represented by certain species in which its individual characteristics are most conspicuous. There are many other species in which these characteristics are less prominent and even obscure. Some confusion in the proper identification of such intermediate forms with one type or another is inevitable. Nevertheless an establishment of additional independent types of structure to take care of these intermediate forms would not seem to improve the system of classification at this time; indeed, it might lead to greater confusion because of the increasing number of conventional boundaries between various types, and overlapping categories.

It is proposed to designate the types of soil structure by the following symbols: the first type (horizontal or platy structure) by two horizontal dashes (=); the second type (vertical or prismatic structure) by two vertical dashes (||); the third type (blocky structure) by a plus sign (+); and the fourth type (granular structure) by zero (0).

CLASSES OF SOIL STRUCTURE

The classes of soil structure are determined by the average size of the aggregates which make up the greater part of the bulk of the soil and, therefore, are the most conspicuous in a given soil. As a unit of classification each class of soil structure represents a taxonomic subdivision of the type of structure. It represents a group of "species" of any given type that are characterized by a similar size of the aggregates. Each type of soil structure is divided into the same classes such as, for example, fine, medium, and coarse, although the corresponding classes of different types differ from one another in characteristics in which one type differs from the others.

The size of the aggregates of the platy structure is determined by the thickness of plates, that is, by the length of their vertical axis, which ranges from less than 1 mm. to more than 1 cm. This axis is a criterion because it is virtually impossible to measure accurately the diameter of the individual unbroken laminae.

The size of prisms is determined by the length of their diameter, that is, of their horizontal axis, which ranges from about 1 cm. to more than 10 cm. In most soils the prisms are broken into irregular fragments of various sizes at

the tops or, most commonly, at their bases, or at both ends. In most instances it is rather difficult, therefore, to measure accurately the length of their vertical axes.

The size of the aggregates of the blocky and granular structure is determined by the length of an average diameter of the blocks or lumps, which range in size from less than 1 mm. to about 1 cm. (granular) and to more than 5 cm. (blocks).

According to their size, the aggregates of different types are divided into five groups. This number is arbitrary, indeed. No distinct natural boundaries exist between any particular groups of aggregates of different sizes. The size of aggregates of every type of soil structure increases gradually from a minimum to a maximum, although the structure of any particular soil horizon may be characterized by aggregates of some particular size. The whole range between the extremes may be divided into any number of arbitrary groups—two, three, five, or more—and perhaps all numbers would be equally good. No particular reasons have yet been found for drawing the dividing line between any two adjacent groups at some particular size limit of the aggregates.

Classification of structural aggregates according to their size and the ranges of variability in size in each group are presented in table 1.

Five classes of soil structure—very fine, fine, medium, coarse, and very coarse—are recognized in this classification. Each class is characterized by the predominance of aggregates of some particular size. It must be remembered, however, that a taxonomic species of soil structure is the structure of a certain horizon or of a part thereof of some particular type of soil. The structure of any horizon usually is not homogeneous as regards the size of aggregates. The range of variability in the size of the aggregates in any given soil horizon may be wider than the ranges which are arbitrarily established for various size groups of them, as presented in table 1. The class of soil structure of any given horizon must be determined, therefore, by the size of aggregates which dominate the general character of this horizon.

The thickness of the laminae of the platy structure and the diameters of prisms of the prismatic structure usually are more uniform than the size of the aggregates of the blocky and granular soil structures. The ranges of variability in thickness of the plates or prisms in a single soil horizon usually are rather narrow and perhaps not much, if any, wider than the ranges of the individual size groups. Variations in size of the aggregates in the soils having either blocky or granular structure are greater than this. The data in table 2 demonstrate the complex character of the structure in several soil horizons.

Some classes of soil structure are more common than others. The very fine, fine, and medium platy structures, for example, are much more common than the coarse and especially the very coarse structure of the same type. This last class of platy structure usually is associated with sedimentary materials, and under these conditions its origin is different from that of the other classes of the type.

On the other hand, the very fine prismatic structure is rather rare. The fine, medium, and coarse prismatic structures are the commonest representatives of this type. The very coarse prismatic structure is not uncommon, but in most instances it represents the vanishing of soil structure, as such, and its gradation into a more or less incomplete breaking of the soil by a series of irregular and predominantly vertical cracks, and finally to a massive, structureless condition (pl. 2, fig. 5).

The blocky structure (third type) grades from very fine to very coarse. The fine, medium, and coarse classes of this type are the most common forms of

TABLE 1

*Classification of the aggregates of different types of soil structure**

CLASS	TYPE			
	Platy =	Prismatic ‖	Blocky +	Granular 0
Very fine aa	=aa <1 mm. 1, 2	‖aa <1 cm. 1, 2, 3	+aa 1–5 mm. 1, 2, 3	0 aa <1 mm. 3
Fine a	=a 1–2 mm. 1, 2	‖a 1–2 cm. 2, 3, 4	+a 5–10 mm. 1, 2, 3, 4	0 a 1–2 mm. 3, 4
Medium b	=b 2–5 mm. 1, 2, 3	‖b 2–5 cm. 3, 4, 5	+b 1–2 cm. 2, 3, 4, 5	0 b 2–5 mm. 3, 4
Coarse c	=c 5–10 mm. 1, 2, 3, 4	‖c 5–10 cm. 4, 5	+c 2–5 cm. 3, 4, 5	0 c 5–10 mm. 3, 4
Very coarse cc	=cc >10 mm. 1, 2, 3, 4, 5	‖cc > 10 cm. 5	+cc >5 cm. 4, 5	0 cc >10 mm. 3

* Figures below the size of aggregates indicate the most common grades of soil structure characterized by aggregates of a given type and a given class.

macrostructure. Like the very coarse prismatic, the very coarse blocky structure, although not uncommon, represents a gradation from a distinctly developed structure to an incomplete fragmentation of the soil material by a series of irregular cracks. The very fine blocky structure represents an extreme fragmentation of the soil material which is rather uncommon under normal field conditions. Usually it develops on the surface of the outcrops of various parent materials. This kind of structure represents a gradation from macrostructure and develops usually in mineral soils more or less free of humus. Certain soils with a relatively high content of organic matter, like certain varieties of chernozem, and especially some Wiesenboden, half-bog, and muck

soils may possess a blocky structure. The very fine and fine classes of this type of structure, however, may be difficult to distinguish from very fine and fine classes of the granular type.

The very fine, fine, and medium classes of granular structure are more common and relatively more homogeneous as regards the average size of the aggregates than is the coarse granular or crumb structure. Some disagreement exists among soil scientists about the character of the very coarse structure of this type. Perhaps the structure commonly referred to as "nutlike" belongs to this group.

TABLE 2

Percentage by weight of the aggregates of different sizes in certain soil horizons

TYPE AND CLASS OF STRUC- TURE	HORIZON	DEPTH	TYPE OF SOIL	PERCENTAGE OF THE AGGREGATES OF DIFFERENT DIAMETERS						
				1 mm.	1-2 mm.	2-5 mm.	5-10 mm.	10-13 mm.	13-20 mm.	20 mm.
		inches								
0 b	A	4–12	Carrington clay loam	18	35	38	8	1	..	..
0 b	A	3–12	Prairie soil, Minn.	26	32	37	5	..	..	..
0 b	A	3–9	Webster clay loam	23	35	33	8	1	..	..
0 b	A	4–10	Prairie soil, Ill.	22	38	31	8	1	..	..
0 aa	A	0–4	Carrington clay loam	64	30	5	1	..	..	..
0 aa	A	0–3	Webster clay loam	59	34	6	1	..	..	..
+a	B	6–12	Hyden loam	4	7	21	41	17	10	..
+b	B	12–18		2	3	7	36	28	24	..
+c	B	18–26		1	2	5	16	14	22	40
+c	B-C	26–36		2	3	7	13	10	18	47
+aa	A$_2$-B	5–8	Nebish clay loam	7	15	49	28	1	..	..
+a	B	8–12		5	15	31	42	5	2	..
+b	B	12–16		2	3	10	31	20	17	17
+aa	B	8–16	Hyden silt loam	6	10	42	38	4	..	..
+a	B	7–14		9	10	27	41	7	6	..
+b	B	15–25	Miami silt loam	4	6	15	28	19	14	14
0 a	A	1–4	Davidson clay loam	26	37	22	9	4	2	..
+a	B	6–12		7	15	38	29	7	4	..

It is proposed to designate the classes of soil structure by letters as follows: aa—very fine; a—fine; b—medium; c—coarse; and cc—very coarse. In the designations of any species of soil structure the class symbol should follow the type symbol, although in verbal descriptions the reverse order should be used. For example: very fine platy structure (= aa), fine granular (0 a), or coarse blocky (+c) structure.

GRADES OF SOIL STRUCTURE

The grade of soil structure refers to its relative distinctness; it is determined by a relative stability or durability of the aggregates and by the ease of their separation from one another.

The durability of the aggregate depends upon the strength of adhesion of the

primary particles within the aggregates, whereas the ease of separation of the aggregates from one another depends upon the strength of adhesion between the adjacent aggregates. The highest grade of soil structure is characterized by the maximum strength of adhesion within the aggregates, and the minimum, if any, adhesion between the aggregates, that is, by the widest ratio between these two kinds of adhesion. The theoretically ideal structure would be characterized by permanently cemented, firm aggregates without any adhesion between them. A gradual narrowing of the ratio between the strengths of adhesion within and between the aggregates, which is manifested in a decrease of durability of the aggregates and in an increase of their attachment to one another, indicates a decrease of distinctness of soil structure or a lowering of its grade. The structure vanishes when the strength of adhesion between the adjacent aggregates becomes equal to that of adhesion of the primary particles within the aggregates. Such a condition is characteristic of structureless soil. The strength of a homogeneous adhesion throughout the mass of a structureless soil ranges from a high degree in massive soil to the vanishing point in loose sandy soil.

Five grades of soil structure are recognized in this classification: the first represents a poorly developed or poorly defined structure; the second, a weakly developed or weakly defined structure; the third, a moderately developed or moderately defined structure; the fourth, a well-developed or well-defined structure; and the fifth, a strongly developed or strongly defined structure.

Identification of the grade of soil structure is made on the basis of particular combinations of grades of durability of the aggregates and degrees of ease of their separation from one another.

Three grades of durability of aggregates—strong, moderate, and weak—are recognized. Strong durability is characteristic of firm or compact aggregates that can be crushed only by considerable pressure or by persistent rubbing. A moderate durability characterizes stable aggregates which can be handled rather roughly without any damage to their shape but which yield easily to pressure or rubbing. A weak durability indicates very unstable, rather soft and fragile aggregates that fall apart very readily even if handled with precaution.

The three degrees of the strength of adhesion between the adjacent aggregates, designated also as strong, moderate, and weak, are distinguished from one another as follows: A strong interaggregate adhesion makes the separation of an individual aggregate difficult. It is necessary to break the lump of soil along its natural cleavages in order to separate the adjacent aggregates from each other. A moderate adhesion allows the separation of the aggregates by a moderate shaking of the lump of soil, by a slight pressure, or by any similar operation. A slight adhesion characterizes a condition in which the soil freely falls apart into aggregates. In many instances, this slight adhesion does not hold the aggregates against the force of gravity and allows them to drop or roll down from steep cuts.

The combinations of the grades of durability of the aggregates and of the strength of adhesion between them which are characteristic of various grades of soil structure are presented in table 3.

The first grade of soil structure is characterized by weakly cemented, soft and unstable aggregates strongly tied to one another. This is the lowest grade and the nearest to the point of vanishing soil structure. The ratio between the strength of adhesion within the aggregates and that of adhesion between adjacent aggregates is very narrow, approaching 1:1. Usually structure of this grade develops in light-textured soils.

The second grade of soil structure is characterized by either moderately cemented aggregates held together by a strong adhesion to one another or by weakly cemented mellow aggregates tied together by a moderate adhesion. The first combination is more common in soils of a medium texture, for example, in silt loams, whereas the second one is characteristic of soils of light texture.

TABLE 3

The grades of soil structure

ADHESION OF THE AGGREGATES TO ONE ANOTHER	CEMENTATION OF THE AGGREGATES		
	Weak	Moderate	Strong
Weak	Grade 3 Moderately developed	Grade 4 Well developed	Grade 5 Strongly developed
Moderate	Grade 2 Weakly developed	Grade 3 Moderately developed	Grade 4 Well developed
Strong	Grade 1 Poorly developed	Grade 2 Weakly developed	Grade 3 Moderately developed

The third grade of soil structure is characterized by one of the following combinations: first, strongly cemented, firm aggregates bound by strong adhesion to one another; second, moderately cemented aggregates, held together by a moderate force of adhesion; or third, weakly cemented, soft, unstable aggregates, loosely attached to one another by weak adhesion. The first combination is typical of heavy soils such as silty clays and clays; the second is more common in soils of medium texture; and the third is common in light and mellow soils rich in silt but rather poor in colloidal material.

The fourth grade of soil structure is characterized either by strong durability of the aggregates and moderate adhesion between adjacent aggregates or by moderate durability of the aggregates and weak adhesion between aggregates. The first combination is more common in heavy soils, whereas the second one is characteristic of soils of medium-heavy texture, such as clay loam and silt loam.

The fifth grade of soil structure is characterized by strong durability of the aggregates and weak adhesion between adjacent aggregates. The aggregates

are firm and rather compact and separate from each other freely. Usually structure of this grade develops in soils of a fine texture. Light-textured soils, such as loams and sandy loams, ordinarily cannot possess such a structure because of the lack of cementing colloidal material.

The second and fourth grades of soil structure are characterized by two different combinations of durability of the aggregates and their adhesion to one another, and the third grade is characterized by three different combinations. Such a variety is due to the difference in texture of the soil materials.

For the purpose of classification of soil structure, all soils can be grouped into the three general textural groups as heavy, medium, and light soils. The first includes silty clays and clays; the second, clay loams, silt loams, and loams; and the third, sandy loams, loamy sands, and sands. The durability of the aggregates depends to a considerable extent upon the texture of the soil and particularly upon the percentage of clay, which acts as the binding material. Consequently the strongly cemented aggregates are formed most commonly in heavy soils, the moderately cemented ones in medium soils, and the weakly cemented in light soils. The grades of soil structure included in the last column of table 3 are characteristic predominantly of heavy soils; the grades comprising the next to the last column are found mostly in soils of medium texture; and those included in the second column are characteristic of the light soils. It follows that the structure of the fifth grade is usually associated with a heavy soil, whereas that of the first grade more commonly characterizes a light soil. Rarely can a structure of higher than the third grade develop in light soils, and usually if any structure develops in a heavy soil it is not lower than the third grade, because if any aggregates are formed in a heavy soil, these aggregates are rather strongly cemented. Any soil, whether heavy, medium, or light, may possess a moderately developed structure but, naturally, the durability of the aggregates of a heavy soil would ordinarily differ from that of the aggregates of a medium or light soil. A determining characteristic of the grade of soil structure is not durability of the aggregates alone but the ratio between the force which determines such durability and the force tending to hold together the adjacent aggregates.

The grade of structure of any particular soil horizon varies with the moisture content. Usually the best defined structure is displayed by the soil in a nearly air-dry condition. An increase of moisture tends to lower the grade of structure in some instances to the vanishing point. Even the most firm and compact aggregates become softer and less stable after wetting. At the same time they swell and press more strongly against one another, thus increasing the interaggregate adhesion. It must be noted that not all aggregates behave in water in the same way; some are more water-stable than others and, perhaps, the most water-stable ones are not those which are most resistant to crushing in a dry state. This, apparently, is due to the difference in solubility of various cementing substances. The extent of variation differs with different soil horizons, sometimes narrowly, sometimes considerably. Yet the extent and

character of the variation, and the character of structure at any particular moisture content, are definite attributes of a given soil horizon. The determination of the grade of structure as a standard characteristic of the soil should refer to the structure of the nearly air-dry soil, although a complete description of the soil should include also notes of its variability under different conditions of moistening.

The grade of soil structure depends also to a large extent upon the pattern of soil porosity. Soil porosity represents the percentage by volume of the bulk of soil which is not occupied by solid matter. The counterpart of porosity is compactness, which represents the percentage by volume of the bulk of soil made up by solid matter. Obviously compactness plus porosity equal the whole bulk of soil. The greater the porosity of a soil, the lower is its compactness and vice versa. The porosity of most soils ranges from about 30 to about 60 per cent and the compactness from about 70 to 40 per cent. The formula used for the calculation of porosity is

$$\frac{S - A}{S} \times 100 = \text{porosity},$$

and that for the calculation of compactness,

$$100 - \frac{S - A}{S} \times 100 = \text{compactness},$$

where S is specific gravity and A is volume weight or apparent gravity.

These definitions refer to the quantitative aspect of porosity and compactness. Morphology, however, is concerned primarily with the qualitative aspects of these characteristics. The qualitative aspect of soil porosity refers to the pattern of the void space in the soil mass, whereas the qualitative aspect of soil compactness refers to the pattern or fabric of the solid phase of the soil body. Essentially the same as regards its percentage, porosity may have a fundamentally different pattern of the pore space in soils of different mechanical composition.

Considering the morphological or qualitative aspect of porosity, one may distinguish three different phases or forms of soil porosity; namely, textural, structural, and specific. The sum total of the different forms of porosity of any given soil material may be designated as the total porosity of such a material.

Textural porosity represents the ratio of the pore space made up of the voids between the primary particles such as grains of sand and silt to the bulk of soil material. The pore space considered in textural porosity does not include any other voids such as cracks, fissures, bubbles, and channels of roots, worms, and insects.

Structural porosity represents the ratio of the pore space made up exclusively of the voids between the structural units, that is, mainly by the cracks and fissures, to the bulk of soil material. This pore space includes neither the

voids of textural porosity within the aggregates nor the voids made by roots, insects, worms, etc. The pattern of structural porosity depends upon the type, class, and grade of soil structure.

Specific porosity represents the ratio of the pore space made up of the voids produced by roots, insects, worms, and other animals, and by bubbles of gases or air to the bulk of soil material. This pore space includes neither the voids between the aggregates nor the voids between the primary particles within the aggregates except for those produced by the aforementioned agencies.

The total soil porosity, the sum total of all these forms, represents a ratio of the pore space made up by all kinds of voids to the bulk of soil. The total porosity of every structureless soil is represented entirely by textural porosity, provided that the soil is free of roots, insect borings, and other voids of specific porosity.

Every individual soil aggregate is a porous body. The total porosity of a single aggregate is also represented by the textural porosity alone, provided that such an aggregate has not been perforated by roots, worms, or insects.

The total porosity of every structural soil which is free of cavities of specific porosity is made up of two phases, one representing the sum total of textural porosity within the aggregates, and the other representing the structural porosity. The ratio of textural porosity to the structural depends upon the type, class, and grade of soil structure and upon the mechanical composition and the moisture condition of the soil.

Lowering of the grade of soil structure by an increase of soil moisture is accompanied by marked changes in the ratio of the textural to the structural porosity. The maximum shrinkage and the maximum structural fragmentation usually are displayed by air-dry soils. Presumably every aggregate shrinks individually. Loss of water apparently is accompanied by a drawing together of the primary particles into a more compact aggregate, thus decreasing the textural porosity. A tighter assembling of the primary particles increases the number of points of contact between adjacent particles at which they can stick to each other and consequently increases the general cementation and rigidity of the aggregate. The shrinkage of the aggregates naturally increases the voids between the aggregates. Consequently the percentage of textural porosity in the total porosity decreases and the percentage of structural porosity increases correspondingly, provided that the total porosity of the soil remains the same at different moisture conditions. The latter is not necessarily true: the drying of the moist soil may be accompanied by its general settling, and in such instances a general decrease of total porosity develops.

During the wetting of the dry soil, a reverse process takes place. Water first fills all the large interconnected voids of structural porosity and displaces the air from these. Very likely it traps a certain amount of air in much smaller voids of textural porosity within the aggregates. Penetrating the aggregates, water apparently pulls apart the primary particles, thus reducing the compactness of aggregates and increasing the textural porosity. Such an

increase takes place on account of the corresponding decrease in structural porosity, provided that the total porosity remains the same. The aggregates swell and gradually close the voids between them.

A thorough soaking of the soil may reduce the structural porosity to the vanishing point; as a result, the proportion of textural porosity in the total porosity approaches 100 per cent. In such a condition the soil loses its structure. The B horizons of many solonetz soils possess a structure of the highest grade (grade 5) in a dry condition and lose it entirely upon being saturated with water.

This relationship between the grades of soil structure and the changes in proportions of the structural and textural forms of porosity suggests a possibility of certain mathematical expressions for various grades of structure.

It is proposed to designate the five grades of soil structure by small numbers 1 to 5 respectively used as a superscript of the letter indicating class of structure, although in verbal descriptions the name of a grade should precede those of the class and of the type. For example:

$$0\ a^4\text{—well-developed fine granular structure}$$
$$+b^5\text{—strongly developed medium blocky structure}$$
$$=aa^3\text{—moderately developed very fine platy structure.}$$

SPECIES OF SOIL STRUCTURE

As taxonomic units of classification the types, the classes, or the grades fail to represent the individual species of soil structure. A species of soil structure is the structure of some particular horizon of a given soil. In addition to the characteristics determining its type, class, and grade, each species of soil structure might possess a number of individual characteristics in which it may differ from the other species of the same type, class, and grade. Such individual characteristics include, for example, coatings on the surface of the aggregates (pl. 2, fig. 6), the color of such coatings, their dullness or glister; the character of some particular facets, such as flatness or roundness of the tops of prisms, the degree of sharpness of the edges; some particular geometrical characteristics such as square, pentagonal, sexagonal, or polygonal prisms, cuboidal or polygonal blocks; difference in color of the upper and lower surfaces of the plates; and flatness or bending of the plates.

Some species of soil structure are so much more common than others that descriptive names have become attached to them. For example, the species of well-developed prismatic structure, characterized by the rounded tops of prisms, usually are referred to as "columnar" structure in contrast to normal prismatic structure, characterized by flat tops of the prisms. The medium or coarse blocky structure, characterized by indistinct or somewhat rounded edges, is usually described as "nutlike" structure. A number of other terms such as "squamose," "pencillike," "polyhedron," "pealike," "scaly," "schistose," "lenticular," "flaky," "starchy," "buckshot," "lumpy," and "cloddy," have been suggested for the designation of various species of structure. Perhaps

such a terminology is sometimes useful. It is obvious, however, that any particular name should be attached only to a definite entity, thoroughly examined and precisely described. Unfortunately very few species of soil structure satisfy these requirements thus far.

SUMMARY

Soil structure is a condition of the soil material in which the primary particles like sand, silt, and clay are arranged into various aggregates. Aggregates differ in shape, in size, in stability, and in a degree of adhesion to one another.

Four principal types of soil structure—platy, prismatic, blocky, and granular—are recognized on the basis of general shape of the aggregates.

The structure of each type is divided into five classes according to the average size of the most numerous and conspicuous aggregates. The classes correspond to very fine, fine, medium, coarse, and very coarse soil structure.

Five grades of soil structure are distinguished as poorly developed, weakly developed, moderately developed, well developed, and strongly developed. Each grade of soil structure is characterized by a particular combination of durability of the aggregates and degree of their adhesion to one another.

The individual forms of soil structure in any taxonomic group differ from one another in various aspects, including character of the surface of the aggregates, sharpness of their edges, coatings, and other less significant characteristics.

PLATE 1

FIG. 1. Fragments of the aggregates of medium platy soil structure (═ b).

FIG. 2. Aggregates of fine prismatic soil structure (‖ a).

FIG. 3. Fine prismatic structure in the B horizon of the light brown soil in the short grass prairie.

FIG. 4. Old exposure of prismatic structure in the B horizon. The prisms on drying, break into irregular blocks.
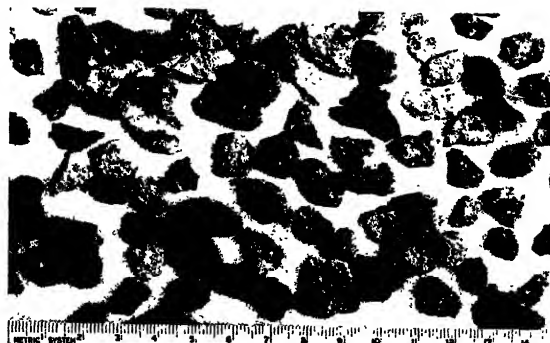
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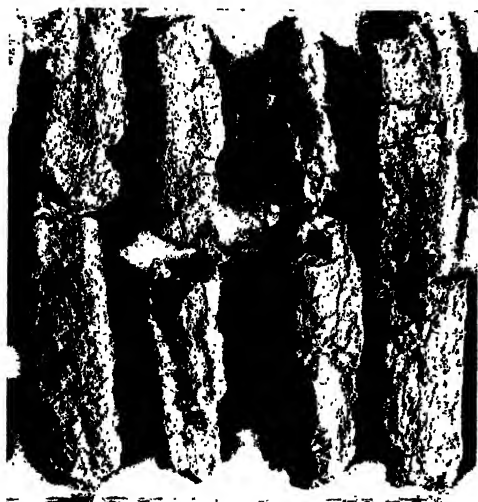
FIG. 1

FIG. 2

FIG. 3

FIG. 4

PLATE 2

FIG. 1. Aggregates of fine blocky (fragmental) structure (+ a).

FIG. 2. Fine blocky structure in the B horizon of podzolized soil.

FIG. 3. Fine granular structure in the A horizon of chernozem (0 a).

FIG. 4. Aggregates of granular structure:

<div style="text-align:center">

a—Very fine

b—Fine

c—Medium and coarse.

</div>

FIG. 5. Coarse prismatic structure of loess.

FIG. 6. Dark coating (skin) on surface of the aggregates (+ b) in the B horizon of podzol. On left are fragments of the same aggregates showing light color of their inner parts.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

AN EXPERIMENTAL STUDY ON THE DEVELOPMENT OF ADOBE STRUCTURES IN SOILS

CHIA WEI CHANG[1]

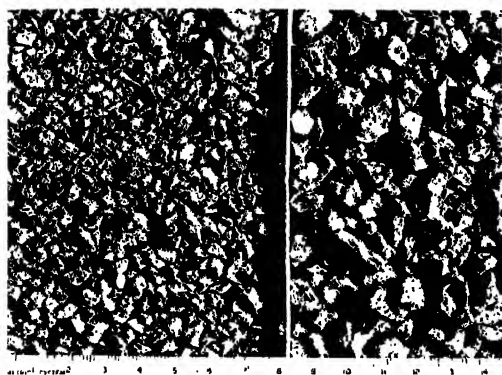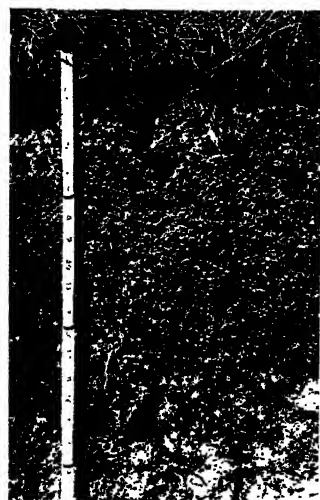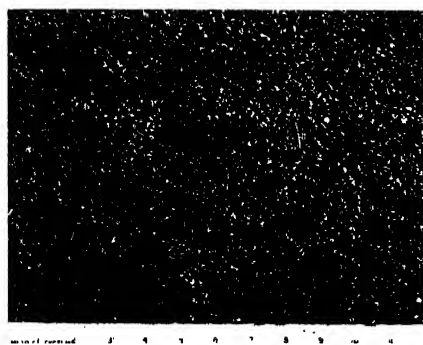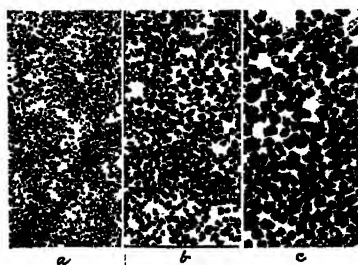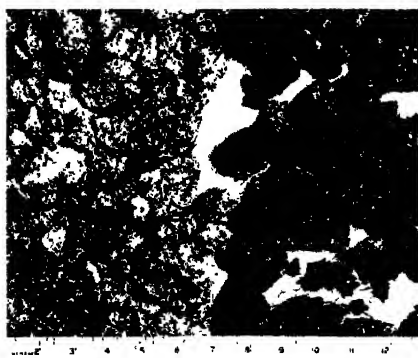*California Agricultural Experiment Station*

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According to Webster's New International Dictionary, the word *adobe* is of Spanish-American or Spanish origin, and refers to unburned or sun-dried bricks or to buildings made of such bricks. Locally, it has been used in southwestern United States as referring to soil from which adobe bricks are made. Soil scientists in California have applied the term to clay soils which crack on drying and form large blocks similar to bricks (pl. 1, fig. 1).

In 1884 Hilgard (5, p. 39) described an adobe soil at Colton, California, as being rich in clay, extremely adhesive when wet, and like dark slate of stony hardness when dry. In 1927 Shaw (9) defined adobe soil as "soil which on drying cracks and breaks into irregular but roughly cubical blocks. The cracks are usually wide and deep and the blocks from 20 to 50 or more centimeters across. Adobe soils are usually heavy textured and high in content of colloidal clay." Smith (11) pointed out that under conditions of intensive drought the blocks may develop secondary cracks. The surface then assumes a buckshot structure.

The purpose of this study was to determine the causes of the formation of adobe structures in soils.

SELECTION OF SOIL SAMPLES

Pairs of soils, one representing typical adobe and the other nonadobe, both from the same or similar series and in most cases from the same general locality, comprise what will be termed, for convenience, "a pair of samples." With the exception of Fargo clay, all soils were collected in California. The following soil series were included: Clear Lake, Marcuse, Stockton, Sacramento, Capay, Ducor, Porterville, Maxwell, Aiken, and Fargo.

PHYSICAL MEASUREMENTS AND CHEMICAL ANALYSES

All soils were subjected to a series of physical and chemical analyses according to standard methods. The results are summarized in table 1. The most significant feature is the lack of correlation between structure and the common

physicochemical properties of the soils. Clay content, moisture equivalent, swelling, base-exchange capacity, Na/Ca ratio, Mg/Ca ratio, pH, organic matter, and vapor pressure curves have similar magnitudes in both adobe and nonadobe soils. A noteworthy exception exists for salinity. High concentrations of electrolytes tend to be associated with nonadobe soils. The crystalline nature of the clay fraction also deserves special consideration: all adobe soils are composed of montmorillonite (7), whereas the nonadobe soils contain a variety of patterns.

TABLE 1

Summarized results of laboratory determinations of physical and chemical properties of adobe and nonadobe soils

TYPES OF DETERMINATION	ADOBE SOILS (8 SOILS)		NONADOBE SOILS (6 SOILS)	
	Average	Range	Average	Range
Swelling...........*per cent*	0.60	0.37 – 0.87	0.48	0.38 – 0.56
<2 μ clay.........*per cent*	46.5	31.0 – 62.7	45.9	33.7 – 66.0
Moisture equivalent *per cent*	35.8	27.5 – 45.5	40.2	32.7 – 55.5
Base-exchange capacity *m.e./100 gm.*	40.3	31.5 – 54.8	35.9	31.0 – 39.8
Total cations...*m.e./100 gm.*	40.8	30.7 – 59.8	37.3*	30.8 – 37.6
Exchangeable Na/Ca.......	0.11	0.11 – 0.25	0.08*	0.005– 0.11
Exchangeable Mg/Ca......	1.78	0.49 – 3.30	2.49	0.22 – 7.10
Concentration of electrolytes at 25 per cent moisture.............*p.p.m.*	1,382	112 –2,480	2,511*	1,200 –5,392 (40,000†)
pH.....................	7.6	5.9 – 8.9	7.8	6.6 – 8.5
Organic carbon.....*per cent*	0.842	0.302– 1.927	1.206	0.968– 1.730
Inorganic carbon...*per cent*	0.080	0.019– 0.126	0.171	0.020– 0.172
Clay minerals.............	montmorillonitic		montmorillonitic kaolinitic mixture	
Vapor pressure curves of moist colloid. Rate of change of vapor pressure (10.0-82.5 per cent) with water content	all small		small great intermediate	

* Does not include Marcuse saline soil.
† Marcuse saline soil.

METHODS FOR QUANTITATIVE MEASUREMENT OF ADOBE STRUCTURES

Though superficial examination indicates that the structural forms within each group may vary in appearance and size, there is one morphological characteristic which seemed to be possessed exclusively by typical adobe soils, namely, the presence of *smooth plane-surfaces* and *angular edges* in secondary structural units. The primary units of nonadobe soils, on the other hand, may at times exhibit blocky structure common to the adobe soils, but when reduced to secondary structural forms they do not consistently show either plane-

surfaces or angular edges. Fracturing the primary units of nonadobe soils always results in rough, crooked, or convex surfaces.

Increasing sphericity (departure from the cubical form) of the aggregates of nonadobe soils may be looked upon as being due either to an increase in the number of plane-surfaces per aggregate, except when the structures are stellate in form, or to the development of the polyhedral or spherical form, in which case the number and magnitude of obtuse angles between the planes would be relatively high. A measure of the shape of the structural forms may be obtained, therefore, either by counting the number of planes per aggregate or by estimating the solid angles of the polyhedral structures. Finally, the irregularity of the surface may be looked upon as an indication of the roundness of the aggregates whose radius of curvature can be measured. Thus the length of the visible contact edge between two or more adjacent aggregates (arc) and the corresponding shortest distance (chord) was measured between the two points which define the beginning and end of the contact edge. The ratio of arc/chord is then used as an expression of shape. Since the terms "arc" and "chord," as here used, are not geometrically exact, the symbols *arc'* and *chord'* are adopted.

The average number of planes per aggregate in the adobe soils is 8.3 $\pm$ 0.58,[2] the angularity is 88.2° $\pm$ 1.18, and the ratio of arc'/chord' is 1.04 $\pm$ 0.07, in contrast to 17.3 $\pm$ 1.70, 121.7° $\pm$ 5.3, and 1.11 $\pm$ 0.09, respectively, for the corresponding measurements on nonadobe soils. The morphological features of the adobe soils as compared with the nonadobe are characterized, therefore, by a small number of planes per aggregate, a low average angularity along the corners of the aggregates, and a low ratio of arc'/chord'.

PHYSICAL CHARACTERISTICS ASSOCIATED WITH TYPICAL ADOBE STRUCTURES

Resistance to crushing

In determining the pressure required to crush air-dry blocks of soil, the ratio of length to diameter of the masses or blocks was standardized to conform to the ratio used by Christensen (4), namely, 3:2.5. The forms thus prepared were crushed in a Carver laboratory press. The pressure required to produce crushing was measured four times for each soil, and the summarized results are reported in table 2 as kilograms per square centimeter. The crushing pressure for the adobe soils ranged from 18 to 45 kgm./cm.[2], with an average of 28.6 $\pm$ 3.96, whereas that of the nonadobe soils ranged from 1 to 6 kgm./cm.[2], with an average of 3.5 $\pm$ 0.27. It is clear that the two groups of soils show a wide difference in resistance to crushing.

Destructible porosity (macroporosity)

Destructible porosity is related to large-sized pores (3) and is defined as the difference between the total porosity of the untreated soil and the total porosity as determined on the puddled soil (microporosity).

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[2] The number immediately after the sign $\pm$ represents the standard deviation.

Table 2 shows that the average porosity destroyed by puddling the nonadobe soils (macroporosity) is approximately six times that of the adobe soils. The average microporosity of these two groups of soils is fairly close.

As indicated in the table, the average microporosity of the artificially puddled adobe soils is fairly close to the average total porosity of the original soils. This relation indicates that adobe soils under natural conditions are already highly dispersed or else they readily become so by the process involved in the determination, whereas the nonadobe soils are either composed of relatively coarse particles or else are flocculated.

Dispersion ratio

The dispersion ratio referred to here is the amount of "less than 2 μ clay" determined without artificial dispersion divided by the total amount of "less than 2 μ clay" after complete dispersion.

TABLE 2

Physical measurements of the macroaggregates of adobe and nonadobe soils

(Mean values and their standard deviations)

SOIL*	RESIST- ANCE TO CRUSHING PRESSURE	DISPERSION RATIO Cd/Ct			>0.5 MM. WATER- STABLE AGGRE- GATES	TOTAL POROSITY	POROSITY DESTROYED BY PUDDLING (MACRO- POROSITY)	POROSITY OF PUDDLED SOIL (MICRO- POROSITY)	TOTAL POROSITY CLAY
		Cd	Ct	Cd/Ct					
	kgm./cm.²				per cent				
Adobe soils...	28.6±3.96	23.3±2.24	46.5±3.86	52.6±6.96	7.6±1.30	27.83±1.16	3.94±0.37	23.89±1.23	0.59±0.08
Nonadobe soils...	3.5±0.27	11.5±2.38	45.9±4.50	25.0±1.86	18.4±0.75	48.50±4.83	22.50±3.30	26.00±2.38	1.06±0.08

* Eight adobe soils and six nonadobe soils were used.

† *Cd* = Percentage of less than 2 μ clay determined without dispersion (Bouyoucos method). *Ct* = Percentage of less than 2 μ clay determined by the International pipette method (ultimate dispersion).

It will be noted from the table that the average dispersion ratio of the adobe soils is 52.6 ± 6.96 per cent. The average for the nonadobe soils, on the other hand, is 25.0 ± 1.86 per cent. The table also shows that the differences in the dispersion ratios are not so marked as the differences of other kinds.

Percentage of water-stable aggregates

In the work reported here, 0.5 mm. was adopted as the critical diameter of water-stable aggregates. As will be noted from table 2 the average percentage for the nonadobe soils (18.4 ± 0.75) is about two and one-half times that of the adobe soils (7.6 ± 1.30). Even the minimum for the nonadobe soils, 12.6, is greater than the maximum of adobe soils, 9.0.

The foregoing suggests that no matter what the mineral constituents of the clay fraction or what chemical compounds are associated with clay soils, as long as their structural forms exhibit plane-surfaces and angular corners, they will be characterized by a high resistance to crushing pressure, a high dispersion

ratio, and a low destructible porosity. Those clay soils which do not possess clearly defined plane-surfaces and angular edges are characterized by low resistance to crushing pressure, low dispersion ratio, and high destructible porosity. These morphological and physical methods appear, therefore, to be capable of characterizing soil structures.

FACTORS INFLUENCING SOIL STRUCTURE

In order to study experimentally the formation of adobe structures as defined in this paper, a number of soils were subjected to various chemical and physical treatments. In all cases the purely morphologic features were substantiated by the determinations of such properties as crushing pressure, dispersion ratio, and destructible porosity.

Effect of electrolytes

Experiments were made to determine the effects produced by removing soluble salts from a saline nonadobe soil (Marcuse clay) and also the effects of adding soluble salt to a nonsaline soil (adobe Stockton clay). Adobe structure was developed in Marcuse clay by removing the soluble salts and allowing the soil to dry undisturbed. It was prevented in adobe Stockton clay (pl. 1, figs. 2 and 3) by the addition of dilute sodium chloride solution.

Effect of calcium carbonate

Calcium carbonate was removed from nonadobe Ducor clay by treatment with N HCl and leaching free from chloride with distilled water, with methyl alcohol, and again with distilled water. After drying, the aggregates developed were sharp-cornered and very firm in consistence. The structure developed upon removal of the lime is, therefore, comparable to that of an adobe soil.

The effects produced by adding lime to a noncalcareous adobe soil were determined on Stockton and Porterville adobe clays. Finely powdered calcium hydroxide was used in quantities of 30, 50, and 100 m.e. per 100 gm. of soil. The limed soils were kept in the greenhouse and irrigated with distilled water as if plants were being grown, the purpose being to convert the calcium hydroxide into calcium carbonate and at the same time to bring about an intimate distribution of fine calcium carbonate particles throughout the soil sample. The experiment was continued from May 10 to August 10. Carbonate was found present after May 21. The changes in physical properties brought about by liming the adobe soils, as expressed by resistance to crushing pressure, are plotted in figure 1. In general the crushing pressure decreased with increases in lime content, the rate of which was most pronounced at low concentrations of lime. It would appear that under the treatment, whenever a change in physical properties, for example, destructible porosity, takes place, there will be a corresponding change in morphological features, such as arc'/chord', of the aggregates.

Effect of organic matter

The removal of organic matter from Fargo clay by H_2O_2 causes the loss of the crumb structure and the development of a structure comparable to that of adobe soils.

An experiment was also made by adding organic matter to adobe Stockton and adobe Porterville clays. The organic matter used was alfalfa, air-dried, ground, and passed through a ½-mm. sieve. The amounts applied were 5, 10, and 15 gm. per 100 gm. of soil. The treated soils were frequently irrigated with distilled water to a moisture content intermediate between the moisture equivalent and saturation under greenhouse conditions. After decomposition
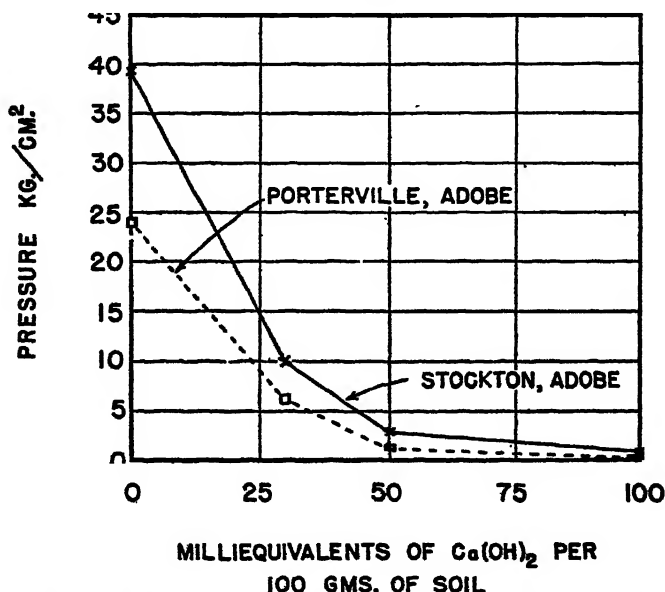
FIG. 1. EFFECT OF LIME ON PRESSURE REQUIRED TO CRUSH SOIL AGGREGATES

the actual amounts of added organic matter remaining in the soil were only 1.2–2.5 gm. for the 5-gm. applications, 2.5–3.8 gm. for the 10-gm. applications, and 3.6–4.8 gm. for the 15-gm. applications. This experiment was begun on February 17 and completed on July 1.

As shown by figure 2, increases in organic matter caused gradual decreases in resistance to crushing pressure. Likewise the size of aggregates decreases and the ratio arc′/chord′ of the aggregates increases. The latter denotes that there must have been a decrease in the angularity of the aggregates (pl. 2).

Although the effects are variable with different soils, it appears that the organic matter influenced the development of plane-surfaces and angular edges of the adobe soils to a greater extent than in the case of the nonadobe soils. These results agree with those of other investigators. It will be noted that the

morphological features of the structures of the treated adobe soils were fairly close to the average of those for the nonadobe soils.

Effect of puddling

Puddling was effected by kneading samples of Sacramento clay, Aiken clay, adobe Porterville clay, and adobe Stockton clay at a moisture content slightly
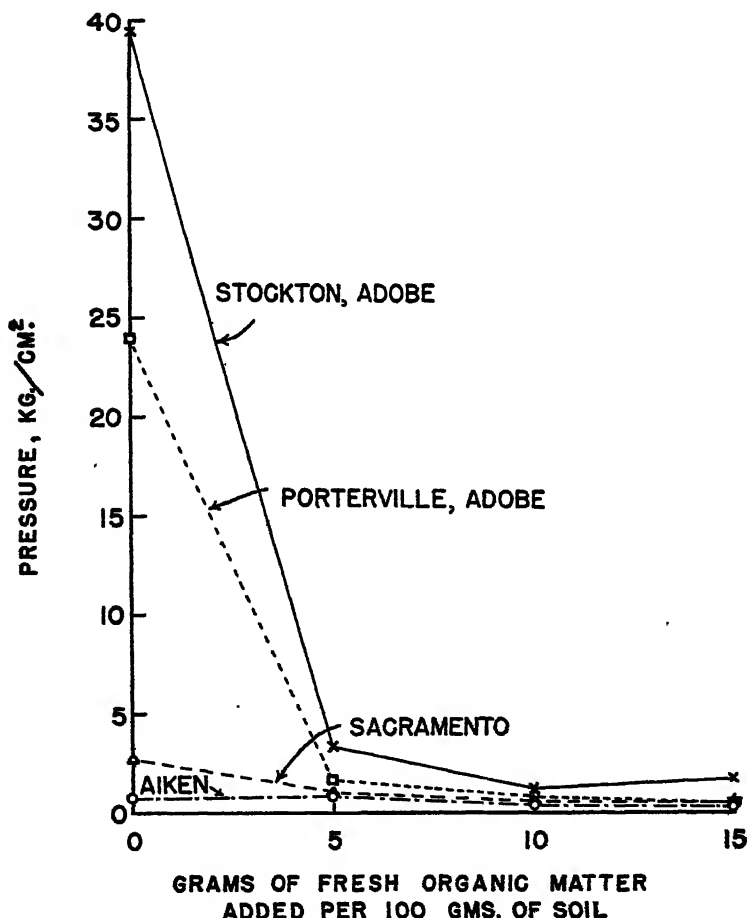
FIG. 2. EFFECT OF ORGANIC MATTER ON PRESSURE REQUIRED TO CRUSH SOIL AGGREGATES

above that of the moisture equivalent. After puddling, all of these soils developed a blocky structure with sharp-cornered edges and plane-cleavages. Other physical properties were also greatly changed by puddling. A large increase in dispersion ratio and resistance to crushing pressure and a great reduction in destructible porosity occurred. This experiment therefore demonstrates that when the granules of nonadobe soils are destroyed the morpholog-

ical structures and the physical properties of these soils become similar to those of an adobe soil.

Experiments were also made on the effects produced by pulverization of the puddled soil after drying. The effect of drying was tested by moistening the pulverized soils and then handling them according to the standard procedure previously used for simulating soil structures. The approximate dispersion ratio and the resistance to crushing pressure were appreciably decreased by the treatment, while the destructible porosity was markedly increased. The mechanical working of the soils in the dry state is effective in restoring the physical properties only to those soils which normally show plane-surfaces and angular edges. It was not effective with the nonadobe soils.

Slow freezing (6) and thawing also were used as means of restoring the structure of puddled soils. On the average, the results brought about by freezing were greater than those achieved by drying and pulverization. The granular structure and porous, friable characteristics of most of the original nonadobe soils were not, however, completely restored.

Effect of wetting and drying

Bouyoucos (2), Sokolovsky (12), and Baver (1) hold that wetting and drying of clay soils are effective means of increasing granulation. Two sets of soil samples were investigated, one kept under laboratory conditions and the other in the greenhouse. The soils in both cases were irrigated and desiccated repeatedly for 3 months. At the end of this period the morphological characteristics and the physical properties of the samples were determined. The results show that the changes produced were generally insignificant except in certain soils kept in the greenhouse. The effect produced by wetting and drying under warm greenhouse conditions is similar to that of freezing soils having a high dispersion ratio, great resistance to crushing pressure, and low porosity. The magnitude of the change is also limited, that is, this treatment does not change an angular structure to a granular structure. Clay soils with well-developed granular structure did not show much response to wetting and drying. The slight changes which did occur were largely toward an increase in dispersion ratio and in resistance to crushing pressure and a decrease in porosity.

Effect of adding sand

Washed quartz sand from 0.1 to 0.25 mm. in diameter was uniformly mixed in several proportions with certain clay soils in order to dilute their clay content. The results show that, as the clay content was reduced, the plane-surfaces and angular edges of the structures gradually disappeared. Laboratory determinations also revealed, in every soil except Aiken clay, a gradual decrease in resistance to crushing pressure as the clay content decreased.

SUGGESTIONS CONCERNING THE FORMATION OF SOIL STRUCTURE

When the particles of a fine-textured soil are largely deflocculated, the soil mass upon wetting tends to become gellike. On drying, the swollen mass

continues to diminish in volume without rupturing until the shearing forces exceed the force of cohesion. As drying proceeds, orientation forces (8, 10, 13) cause the hydrated clay particles to assume a systematic and compact arrangement. On the other hand, aggregates, which are water stable, are formed
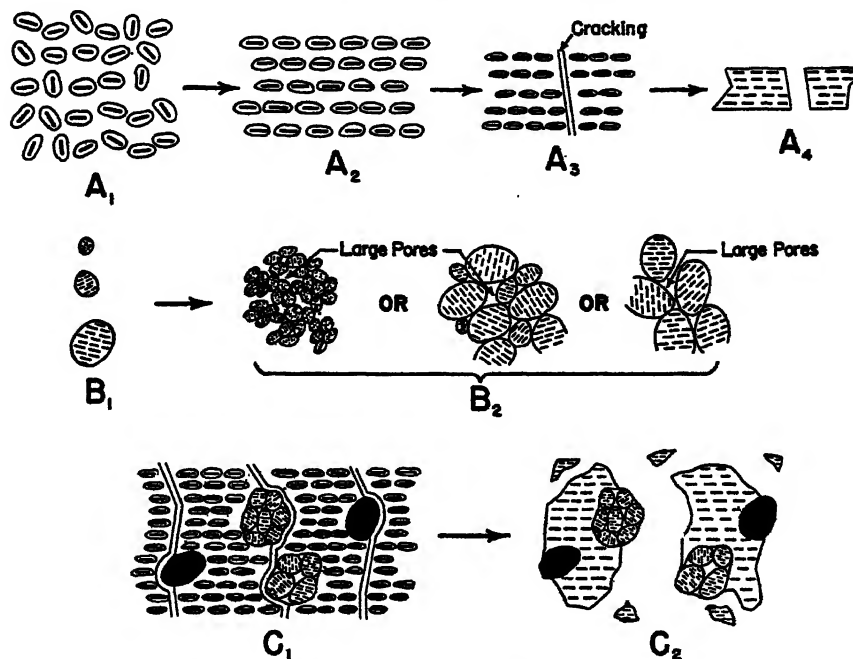
FIG. 3. DIAGRAMMATIC REPRESENTATION OF THE FORMATION OF VARIOUS KINDS OF
SOIL STRUCTURE

Drying from dispersed state: A_1—Beginning of orientation of clay particles (individual particles act as units); A_2—A relatively compact and uniform arrangement of particles as the result of orientation; A_3—Formation of smooth and straight primary cracks; A_4—Formation, on further drying, of dense and firm aggregates possessing smooth plane-surfaces and angular edges.

Drying from flocculated state: B_1—Individual floccules, each of which consists of a large number of orderly arranged particles (floccules or clusters of floccules act as units); B_2—Porous, friable, and water-stable aggregates, each of which consists of a group of floccules.

Drying of mixture of dispersed and flocculated clay, and/or coarse particles: C_1—Fracturings either curved or stopped as the grains become coarser (the width of cracking is not uniform and in general is diminished or unnoticeable because of the increasing heterogeneity and decreasing shrinkage of the system); C_2—Irregular forms of lumps and nutlike aggregates exhibiting slightly variable but intermediate characteristics as compared with those of A_4 and B_2.

when the fine-textured soil particles undergo flocculation previous to drying. The relative amounts of dispersed and flocculated particles may affect the configuration of the soil structure formed upon drying, as follows:

When the particles are dispersed and oriented, the system tends to be relatively homogeneous and the development of differential shrinkage forces will be limited. The primary

cracks will therefore be relatively wide, smooth, and straight. The macroaggregates formed under this condition consequently will possess smooth plane-surfaces and angular edges (fig. 3, A) with higher cohesion and lower porosity than aggregates of heterogeneous particles.

When the soil is flocculated or is predominantly composed of coarse particles, the system will not be homogeneous in respect to the arrangement of the particles and the number of points of contact between particles, and consequently the porosity will be relatively great and the force of cohesion will be relatively small and unevenly distributed. Upon drying, shrinkage will take place, resulting in the formation of many small and irregular cracks in the soil mass. The amount of shrinkage depends not only on the shrinkage coefficient but also on the volume of the aggregates undergoing shrinkage. When the volume of each aggregate is small, total shrinkage is relatively low. Such aggregates tend, therefore, to be porous, friable, and without angular outlines (fig. 3, B and C).

If this reasoning is sound, any factor which tends to produce flocculation of the soil particles and promote granulation should tend to modify the structure toward lumpy, crumb, or granular. Dispersion or deflocculation of clay particles should modify the structure in the direction of increased angularity.

SUMMARY

Many fine-textured soils will crack on drying and break into large irregular blocks. These primary blocks may fracture further and produce secondary macroaggregates of variable sizes (2–10 cm. diameter). If these macroaggregates have smooth cleavage planes and angular edges, the soils possess typical adobe structure.

It has been shown that the presence or absence of typical adobe structure is not correlated with particle size distribution; swelling and shrinkage; moisture equivalent; base-exchange capacity; absorbed Ca, Mg, or Na; pH; vapor pressure curves of the colloidal fraction; or type of clay present.

Typical adobe structure appears to be distinguished by relatively great resistance to crushing pressure, low destructible porosity, high dispersion ratio, low percentage of water-stable aggregates, and high angularity of the macro-aggregates. The gradual disappearance of smooth cleavage planes and angular edges in adobe soils indicates a gradual decrease in resistance to crushing pressure and dispersion ratio, or an increase in aggregation ratio, destructible porosity, and the number of water-stable aggregates.

Amount, type, and colloid-chemical condition of the clay control the development of structures on drying. Other things being equal, a large amount of montmorillonitic clay in soils will tend to give rise to adobe structure, whereas a small amount of total clay or a large amount of kaolinitic clay or even of flocculated montmorillonitic clay will give rise to nonadobe structures. Kaolinitic clays, if properly dispersed, however, also may develop macroaggregates having smooth plane-surfaces and angular edges and, therefore, may also produce adobe structure.

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PLATE 1

FIG. 1. Vertical and horizontal cracks in typical adobe soil.

FIG. 2. Simulated structure of Stockton adobe clay. Relative size of blocks indicated by the 6-inch rule.

FIG. 3. Nonadobe structure of Stockton adobe clay after addition of sodium chloride. Relative size of particles indicated by the 6-inch rule.
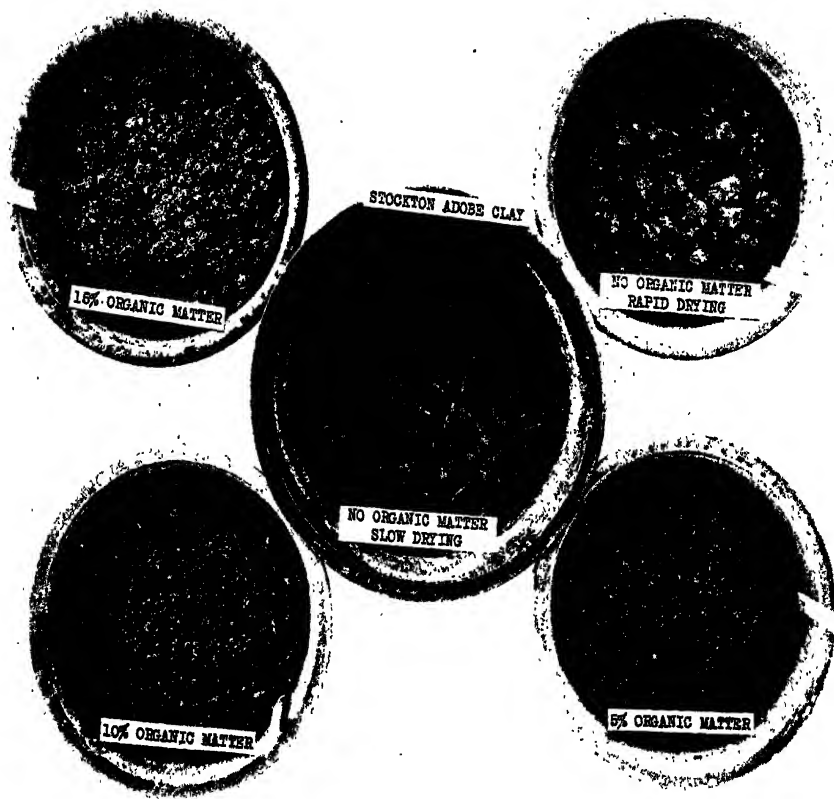
Fig. 1

Fig. 2

Fig. 3

PLATE 2

EFFECT OF THE ADDITION OF ORGANIC MATTER ON THE FORMATION OF ADOBE STRUCTURE IN
STOCKTON ADOBE CLAY

STOCKTON ADOBE CLAY

15% ORGANIC MATTER

NO ORGANIC MATTER
RAPID DRYING

NO ORGANIC MATTER
SLOW DRYING

10% ORGANIC MATTER

5% ORGANIC MATTER

SOME EFFECTS OF VOLUME RATE OF SOLUTION SUPPLY AND OF POTASSIUM CONCENTRATIONS ON THE GROWTH OF WHITE CLOVER[1]

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The regularity with which the plant roots are bathed with a soil solution that contains an adequate concentration of all the essential nutrients is an important factor in the production of strong, vigorous plants. The importance of regularity of volume rate and of concentration as distinct solution characteristics has been stressed by Johnston and Hoagland (4). They reported that no increase in growth of tomato plants resulted from increasing the volume supply of a flowing solution having a high initial concentration of potassium, whereas a marked stimulation of growth resulted from increasing the volume rate with a solution of low potassium concentration. Barnette (1, 2), working with wheat, concluded that within certain limits the dry weights of plants increase directly with the increase in volume of the nutrient solution. Robbins (5) reported that deficiencies of nutrients, especially nitrogen, greatly limited the growth of tomato plants when a solution having an osmotic pressure of 0.08 atmosphere was supplied at the rate of 1 liter daily, but when 4 liters of the same solution were applied each day, good vegetative growth was produced.

The following study is an attempt to determine, first, the effect of various potassium concentrations and, secondly, the influence of volume rate of solution supply on the culture and yield of white clover grown under greenhouse conditions. White clover was used in these studies because it responds markedly to potash applications by an increase in vegetative growth and because extreme potassium starvation symptoms are easily identified on its leaflets.

PLAN OF THE EXPERIMENT

Open-pollinated commercial Ladino white clover seeds were germinated in a half-and-half sand and soil mixture. When the seedlings were 12 days old, they were transplanted into washed quartz sand in 2-gallon glazed pots. Twelve uniform seedlings were planted in each pot and were supplied with a standard nutrient solution for 1 week. The number of seedlings per culture

was then reduced to eight, and the treatment solutions containing potassium concentrations at the various levels indicated in table 1 were substituted for the standard nutrient solution. The total osmotic concentration of each of these treatment solutions as prepared was approximately 0.25 atmosphere, and the initial pH value was 5.2. The cultures were divided into two groups, designated as series 1 and series 2, and placed on a greenhouse bench in two adjacent rows. Each culture in series 1 was supplied with 1 liter of nutrient solution daily, while the corresponding culture in series 2 was supplied with 4 liters. The nutrient solutions were supplied to the cultures from reservoirs by the continuous flow method described by Shive and Stahl (6). Each culture was flushed once every 2 days with its respective solution. This procedure prevented the concentration of the nutrient salts through water loss by evaporation and transpiration, and maintained the pH of the solution that bathed the plant roots at a uniform range of concentration.

TABLE 1

Composition of nutrient solutions

SOLUTION NUMBER	POTASSIUM CONCENTRATION	NUTRIENT SALTS*			
		K_2SO_4	$MgSO_4$	$Ca(NO_3)_2$	$Mg(H_2PO_4)_2$
	p.p.m.	*Partial volume molecular concentration*			
1	1	0.000014	0.00175	0.0045	0.00225
2	4	0.00006	0.00124	0.0045	0.00225
3	16	0.00025	0.00074	0.0045	0.00225
4	64	0.00100	0.00025	0.0045	0.00225
5	256	0.00400	....	0.0045	0.00225

* Boron, iron, manganese, and zinc were added at the rate of 0.25, 0.1, 0.1 and 0.1 p.p.m. respectively.

The response of the plants to volume rate of solution flow and to potassium concentrations was measured in terms of the green and the dry weights of tops and roots and by noting any potash deficiency symptoms or retarded growth rates. The first cutting of tops was made on April 11 when the plants were 1 month old, and a second clipping was made and the roots were harvested on May 15. The tops and roots were oven dried at 70°C. for 24 hours before dry weights were determined. The root weights have not been reported, since they follow the same general trend as do the weights for the tops.

EXPERIMENTAL RESULTS

The results for the green and the dry weights of the top growth and the percentage increases in yield due to volume rate are presented in table 2. Increasing the volume rate of flow of the solutions containing 1, 4, and 16 p.p.m. of potassium, stimulated the growth response of white clover as measured by green and dry matter accumulation. (See also plate 1, figure 1.) Increased

volume rate of solution flow had little effect on the growth rate or on the yield of the plants supplied with 64 or 256 p.p.m. of potassium. It appears, therefore, that volume rate of solution flow was particularly significant, from the standpoint of clover yield, when the potassium concentrations of the solutions

TABLE 2

Percentage yields and moisture content of clover tops as affected by volume rate of solution flow

SOLUTION NUMBER	POTASH	GREEN WEIGHT OF TOPS		INCREASE IN YIELD DUE TO VOLUME RATE	DRY WEIGHT OF TOPS		INCREASE IN YIELD DUE TO VOLUME RATE	MOISTURE PERCENTAGE	
		1-l. Flow Series 1	4-l. Flow Series 2		1-l. Flow Series 1	4-l. Flow Series 2		1-l. Flow Series 1	4-l. Flow Series 2
	p.p.m.	*gm.*	*gm.*	*per cent*	*gm.*	*gm.*	*per cent*	*per cent*	*per cent*
1	1	23.7	61.5	159	5.0	10.8	116	78.9	82.4
2	4	60.6	94.5	56	10.8	14.9	38	83.8	84.2
3	16	171.3	245.1	43	29.3	33.2	13	82.9	86.4
4	64	252.0	274.5	9	33.5	34.3	2	86.7	87.5
5	256	339.3	319.9	...	45.8	43.8	...	86.5	86.3

TABLE 3

Notes on potash-deficiency symptoms and relative vigor of white clover plants supplied with varying concentrations of potassium in the nutrient substrate at volume rates of 1 and 4 liters daily

SOLUTION NUMBER	POTASH *p.p.m.*	DESCRIPTION OF POTASH-DEFICIENCY SYMPTOMS	VIGOR OF GROWTH
Series 1—One liter of solution daily			
1	1	Heavy infestation of white to grayish leaf spots	Poor
2	4	Numerous white to grayish brown leaf spots	Medium
3	16	Only a few leaf markings	Good
4	64	No markings on leaves	Very good
5	256	No markings on leaves	Excellent
Series 2—Four liters of solution daily			
1	1	Numerous white to grayish brown leaf spots	Medium
2	4	Only a few leaf markings	Fair
3	16	No markings on leaves	Very good
4	64	No markings on leaves	Excellent
5	256	No markings on leaves	Excellent

were low, and of minor importance when the potassium concentrations were high. These results are in agreement with the conclusions of Barnette (1, 2), Johnston and Hoagland (4), and Robbins (5) as previously described.

Table 2 further shows that the growth rates of the white clover, as indicated

by both the green and dry weights, increased as the concentrations of potassium in the substrate were raised. This increase in growth rate can be observed in plate 1, figure 2. The highest yields from these plants occurred with the treatment of 256 p.p.m. of potassium, indicating that the maximum growth response to potassium concentration had not yet been reached.

The data in table 2 also show that the moisture content of the plants was greater when the high concentrations of potassium were supplied than when low concentrations were added to the substrate. Hartt (3) noted similar results with sugar cane. Furthermore, at the lower potassium concentrations, increased volume rate of nutrient supply also increased the percentage moisture content of the clover plants.

Additional evidence of the significance of increased volume rate of solution supply from a physiopathic standpoint is presented in table 3. Potash-deficiency symptoms were found on the plants supplied daily at the rate of 1 liter with solutions containing 1, 4, and 16 p.p.m. of potassium. When 4 liters of these same solutions were supplied daily, the deficiency symptoms were greatly reduced at 1 and 4 p.p.m. of the potassium treatments, and had completely disappeared in the culture supplied with 16 p.p.m. of potassium.

SUMMARY

Increasing the volume rate of nutrient flow daily from 1 liter to 4 liters of solutions containing 1, 4, and 16 p.p.m., of potassium respectively, increased the yield of tops of Ladino white clover. Volume rate of flow of the solutions containing 64 and 256 p.p.m. of potassium, however, had no apparent effect on the growth rate or on the yield of the clover plants.

Potash-deficiency symptoms were found on the white clover leaves at the concentrations of 1, 4, and 16 p.p.m. of the potassium treatments in the substrate solution, when the solution was supplied at the rate of 1 liter each day. On the other hand, when 4 liters of solution with like potassium treatments were supplied daily, the deficiency symptoms were greatly reduced at 1 and 4 p.p.m. and were eliminated at 16 p.p.m. of potassium treatment.

Both the green and the dry weights of the tops of Ladino white clover were increased when the concentrations of potassium in the substrate were raised through the treatment range from 1 to 256 p.p.m.

The moisture content of the Ladino white clover plants was greater when high concentrations of potassium were supplied to the substrate than when low concentrations were added. An increase in volume rate of the solutions containing dilute potassium concentrations raised the moisture content of the top growth.

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PLATE 1

EFFECTS OF VOLUME RATE OF SOLUTION SUPPLY AND OF POTASSIUM CONCENTRATIONS ON
GROWTH OF LADINO WHITE CLOVER

FIG. 1. Cultures 1a and 1b received 1 p.p.m. of potassium and cultures 2a and 2b received 4 p.p.m.   Cultures 1a and 2a received only 1 liter of solution daily; the other two cultures received 4 liters.   Note the difference in growth due to volume rate between cultures 1 and 2.

FIG. 2. The complete series 1, which received 1 liter of solution daily.   The potassium supplied to each culture was as follows: 1 = 1 p.p.m.; 2 = 4 p.p.m.; 3 = 16 p.p.m.; 4 = 64 p.p.m.; and 5 = 256 p.p.m.   The growth rate of the white clover increased as the concentration of potassium in the nutrient solutions was raised.

FIG. 2

THE IMPORTANCE OF SODIUM FOR PLANT NUTRITION: I.

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The importance of sodium for plant nutrition is an entirely different matter from a botanic-physiological point of view than from an agricultural point of view. The changing appreciation of sodium, evidenced in the literature since 1860, is, therefore, directly connected with the importance attached either to the physiological or to the agricultural investigations. [See the critical study of the old literature by Blanck (3).]

Plant physiologists find it difficult to ascribe to sodium an independent significance for the plant, because this element, in itself, is not an indispensable nutrient. This has been demonstrated, among others, by Knop (14) in his well-known water cultures of various plant species; by Dehérain (5) with beans and potatoes; by Nobbe and Siegert (20) with buckwheat; by Stohmann (31) with maise; and by Wolff (39) with oats. All these crops could be grown completely normally in sodium-free nutrient solutions. In the plant species investigated so far there has been, therefore, no question of indispensability that would manifest itself, in case of a shortage of sodium, by deficiency symptoms. Even though complete exclusion of traces of sodium in these experiments may be doubted, it is clear that the element in this sense has no direct importance as a plant nutrient and cannot be compared, for instance, with potassium.

The question assumes a different aspect when one takes into account not only the presence or absence of deficiency symptoms, but also the effect on yield and quality, in other words, the agricultural importance, of sodium. In many instances this element unquestionably exercises a beneficial effect on the growth of plants.

It is especially thanks to Wagner (36) that attention was drawn to this favorable influence of sodium, and on his research were based many further investigations. Wagner's research was inspired by his observation that sulfate of ammonia, in many instances, failed to produce yields comparable to those obtained with nitrate of soda, although equivalent quantities of nitrogen were applied. His explanations are particularly noteworthy, because he realized that the value of a nitrogenous fertilizer is determined not only by its content of nitrogen and the form in which this element is present, but also by the effect of the secondary ions. He wondered whether the different results could be due to the sodium contained in nitrate of soda as a secondary element, for, as he reasoned, sulfate of ammonia adds a certain quantity of sulfuric acid to the soil together with a certain quantity of nitrogen (in ammoniacal form),

whereas nitrate of soda adds with the equivalent quantity of nitrogen (in nitric form) a certain quantity of sodium. Naturally, at the time of his investigations, Wagner did not take sufficiently into account the physiological and alkaline reactions, but he endeavored to prove, by means of addition of sodium chloride to sulfate of ammonia, that the sodium effect was the point of issue. He could not prove this in all instances [see Blanck (3, pp. 513–514)], but he succeeded in doing so for such crops as barley, carrots, and fodder beets.

Later investigations furnished more evidence of the effect of sodium and disclosed the conditions under which this is shown to full advantage. It appeared that this effect is partly dependent on the potassium level of the growth medium, and it is in this connection, therefore, that the problem can best be treated. On the other hand, the effect of sodium on certain crops is more pronounced than that of potassium, and therefore one must always be cautious in generalizing the conclusions. To illustrate this with a few typical examples, let us consider three crops—potato, oats, and beet—which show very different responses to sodium.

EFFECT OF SODIUM ON CERTAIN CROPS

Potato

The potato is among the crops with the highest potassium requirement but is distinguished by its capacity to utilize a large part of the potassium available in the soil. In this respect, it occupies a place between cereals and sugar beets. Sodium, on the other hand, is assimilated with difficulty by the potato. The results of the many experiments made with sodium applications to potatoes were not invariably favorable. The application of sodium and potassium salts high in chlorides did produce extra yields, but the production of starch and dry matter declined without exception (24, p. 76). These effects, however, appeared to be due to the chloride ion, which is strongly assimilated by the potato plant. They may not therefore serve as a basis for conclusions with regard to sodium.

When sodium is added in another form, moderate quantities may increase the production of dry matter, as demonstrated by Metz (19) with sodium sulfate and by Süchting (34) with sodium carbonate. The assimilated sodium is present chiefly in the foliage, where, according to Metz, it replaces part of the potassium, which is thus released for the tuber. Maschhaupt (18) obtained very favorable results also with a dressing of $NaNO_3$ to potatoes.

Oats

Though oats have a lower capacity than potatoes to assimilate potassium, the difference in the ability of this crop to assimilate potassium, on the one hand, and sodium, on the other, does not appear to be so great. The available data in the literature indicate almost unanimously that sodium (in most cases NaCl) can markedly increase yields. That oats were favored for a demon-

stration of this effect is evidenced by the fairly large number of investigations in water cultures (2, 9, 15, 39), sand cultures (1, 10, 15, 22, 37), and soil cultures (30). Pfeiffer and his associates (14) have assumed that in oats, also, sodium has the capacity to set free a certain quantity of potassium in the straw and to divert it to the grains.

Beet

Compared with other crops, the various types of beets rank first in capacity to assimilate the potassium available in the soil, and they are likewise superior in capacity to assimilate sodium. We also find in beet the most pronounced example of sodium effect, which could also be explained by the halophytic character of these plants. In view of the special place occupied by beet in this connection the relevant literature is discussed here at greater length.

As early as 1865, Voelcker (35) investigated the effect of NaCl and crude potash salts on soils poor in potassium. In addition to the extra yields produced by these salts, the different treatments resulted in differences in color. As he said: "The leaves of the mangolds dressed with salt had a decidedly lighter color than the rest; those dressed with potash salts were somewhat darker and less yellow in hue and where no top-dressing was applied the leaves had a darker, more bluish-green color, inclining to purple."

Later investigators agreed, in the main, that sodium dressings (NaCl) to beet in the field produce favorable yields (4, 6, 13, 16, 23, 27, 32, 33, 38). There is less unanimity in respect to the sugar content, as pointed out by Schmalfuss (24, p. 76). Of the experiments carried out with nitrate of soda, those of Wagner (36) have already been mentioned, and some other experiments will be referred to in a later paper of this series.

From extensive experiments with sugar beet (variety Hilleshög) in water, sand, and soil cultures, Van Schreven (25) concluded that sodium has a beneficial effect, particularly in cases of a distinct shortage of potassium, a fact which was also stressed in previous publications. He also found that NaCl exercised a favorable effect both on the fresh and dry yields and on the content of sugar, as shown in figure 1.

These experiments also showed that NaCl dressings, in most instances, slightly reduced the K content of foliage and root. The absence of symptoms of K deficiency, in case of K shortage, must be ascribed, therefore, to the higher content of Na. The sodium is conveyed chiefly to the oldest leaves.

Van Schreven (26) was able to demonstrate also that sodium sulfate had a distinctly favorable effect, not only on the outward appearance of the plants with a shortage of potash, but also on the yield of foliage and root and on the proportion and weight of sugar. As in the case of NaCl dressings, this effect became smaller as more potash was available.

The investigations by Van Ginneken and Bruinsma (7) are important because similar results were attained by a different method. These workers

analyzed statistically the results of numerous field experiments, and Van Ginneken (8) showed graphically the relation of these data to yields, fresh root weight, fresh foliage weight, and sugar weight. In this way the various nutrient elements (K, Na, Ca, Mg, N, P, Fe, Mn) were evaluated, and conclusions could be drawn with regard to the fertility of the trial fields. Both of these workers consider sodium important for beet: "For an adequately abundant development of foliage a fair quantity of sodium is presumably always necessary, *even though a proper quantity of potassium is present.* If there is not sufficient potassium available, the presence of sodium is of the greatest direct importance for a satisfactory crop."
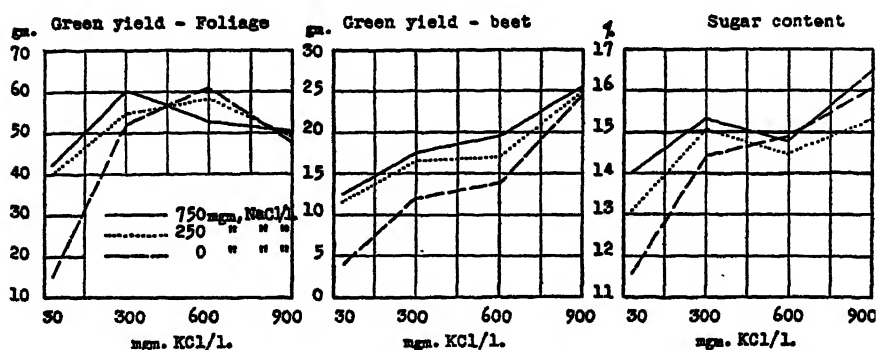
FIG. 1. GREEN YIELD OF FOLIAGE AND OF ROOT AND SUGAR CONTENT OF SUGAR BEETS GROWN IN WATER CULTURES WITH INCREASING QUANTITIES OF POTASSIUM AND SODIUM CHLORIDES
After Van Schreven (25)

The fact that the assimilation of sodium by beet may be very considerable is clearly apparent from data gathered by Van Itallie (12), who investigated for some types of fodder beet with different contents of dry matter the assimilation of sodium and potassium and compared this at successive stages and under varying fertilizer treatments with the assimilation by sugar beet. The difference in assimilation capacity is apparent from the following figures:

	CONTENT OF COMPLETE BEET PLANTS AT HARVEST		
	Dry matter	K	Na
	per cent	*m.e.**	*m.e.**
Productiva	12	78	43.5
Ovana	14	71.5	35.5
Eureka	16	64	31.5
Friso	18	64.5	32
P. Kühn (sugar beet)	..	45.5	24.5

* Per 100 gm. dry matter.

A remarkable aspect of these results is that the various types do show a large difference in assimilation, but the ratio K:Na is almost constant for the various classes of dry matter. Van Itallie concluded that in the types of beet with the highest content of water, sodium can take over a large part of the potassium functions both in the root and in the foliage, but that in beets containing a high percentage of sugar, sodium is important only for the production of foliage rich in water.

The foregoing examples indicate that as the capacity to assimilate sodium increases, the importance of this element for potato, oats, and beet also increases. More crops could be added to this list. Barley, for instance, behaves in about the same way as do oats: the capacity to assimilate potassium is relatively slight, and that for sodium differs but little. As with oats, it was demonstrated for barley that sodium can increase yield [see for instance (21)]. Other crops sensitive to sodium dressings include mustard, peas, flax, and various types of cabbage.

IMPORTANCE OF SODIUM IN RELATION TO POTASSIUM

Let us now revert to the point at issue, namely, the importance of sodium for the plant. As there has been no evidence so far of a specific function of sodium, an effort was made to determine the importance of sodium in relation to that of potassium. In the crops already discussed, it appeared that in the event of a potassium shortage most of the sodium went to the foliage, where it set free a certain quantity of potassium for use in other parts of the plant, such as the tuber of the potato, the grains of oats and barley, and the root of the beet. According to Van Itallie, sodium would also play a part in the root of fodder beet; and Van Ginneken has asserted that a certain quantity of sodium is always desirable in the foliage of beet. This suggests the idea of an independent function in the plant.

Maschhaupt (17) investigated the mutual replacement of cations in the plant, both in general and in particular with regard to potassium and sodium, and as a result introduced the concept of equivalent replacement, a concept found only occasionally in the older literature. He found that in many instances the total number of milliequivalents per 100 gm. dry matter was almost constant for two, three, or four of the cations, a fact which seemed to confirm the theory that some cations can actually take over the functions of others within certain limits. He ascertained an approximately equivalent replacement of potassium and sodium in fodder beet, oats, barley, and white mustard, and to a less extent in flax. In potatoes and caraway, on the contrary, there was no evidence of equivalent replacement. His investigations showed at the same time that K could partly be replaced in some other crops by calcium and magnesium.

Although Maschhaupt's findings may not have universal application, inasmuch as the sum total of the milliequivalents of Ca, Mg, K, and Na for any

one crop is not constant on all types of soil, they serve, nevertheless, to show that only certain crops have the capacity of assimilating the sodium presented.

The following averages and ratios computed from figures gathered by Maschhaupt give a rough idea of the assimilation capacity of a few crops:

CROP	MILLIEQUIVALENTS PER 100 GM. DRY MATTER (FOLIAGE)			Na	$\frac{Na+K}{Ca}$
	K	Na	Ca		
				per cent*	
Fodder beet..........................	90	150	90	45	2.6
Oats.................................	56	35	19	32	4.8
Hay.................................	51	15	31	15	2.1
Flax.................................	34	13	28	17	1.7
Potato..............................	100	6	83	3	1.3
Peas.................................	26	11	142	6	0.3
Caraway.............................	47	6	74	5	0.7
Red clover..........................	47	9	98	6	0.6

* Of the total milliequivalents of K, Na, Ca.

These figures cannot, of course, be regarded as standards, because the contents fluctuate too much and are based on limited data only. Nevertheless, in the first four crops, the absolute as well as the relative sodium content is high. The relative content of the other crops fluctuates between 3 and 6 per cent only. It is not surprising, therefore, that potato, for instance, shows a much weaker reaction to sodium applications than does beet.

A few other figures show the same situation. Van Itallie (11) carried out pot trials on a poor acid soil with three different fertilizer treatments: first, no N or K; second, 10 kgm. Na per hectare, in the form of Na_2SO_4; third, 10 kgm. Na and 10 kgm. K per hectare, in the form of sulfate. He found the following content of sodium, in milliequivalents per 100 m.e. nitrogen in the dry matter:

CROP	NO Na OR K	Na_2SO_4	$Na_2SO_4 + K_2SO_4$
Wheat...............................	1.2	1.7	1.0
Potato..............................	1.4	1.4	2.0
Oats................................	2.8	10.3	6.2
Canary grass........................	5.7	11.3	5.2
English ryegrass....................	4.7	11.5	8.5
Serradella..........................	6.5	12.6	13.1
Mustard.............................	11.9	22.5	16.8
Beets...............................	37.7	77.2	70.0

The K content of these crops varied between 20 and 40 m.e. Wheat and potatoes, both less sensitive to sodium dressings, again appeared to be among the crops assimilating least sodium.

DISCUSSION

In the foregoing we have adopted the view that the effect of sodium is a direct one, that is, the plant assimilates sodium and this exercises a certain function. The literature also offers another explanation, namely, that sodium has an indirect effect, in that, by interchange, it would set potassium free in the soil and consequently increase the level of available potassium. Though this possibility cannot be entirely excluded, it certainly cannot be of primary importance, as it is within the plant. Moreover, it is not clear at the present stage of scientific progress how the liberation of potassium could take place, for, if potassium is available in an easily exchangeable form, it will be at the disposal of the plant without the action of sodium. If potassium is fixed more firmly, for instance in the mineral lattice, it is difficult to imagine its being set free by sodium, because the sodium ion cannot occupy the place of potassium in the crystal lattice, such as in clay minerals. Schulze (28, 29) found that sodium cannot set potassium free, but that, on the contrary, potassium does set sodium free from zeolitic compositions. In our opinion there may be, at most, an effect of secondary importance. Accordingly, the importance of sodium refers chiefly to its functions *in the plant*. It is still difficult to judge whether this function concerns exclusively replacement of potassium, for which an equivalent replacement is only possible in part, or whether we are dealing with a certain independent importance of sodium. Subsequent papers of this series will show that calcium cannot be disregarded in this connection either. The problem, in our opinion, is therefore rather a question of equilibrium of cations than of a separate sodium-potassium relationship.

SUMMARY

This paper points out once again that, even though without a *specific* function, sodium is certainly important from an agricultural point of view. Sodium cannot, of course, be considered as important as potassium, because of the greater physiological value of the latter, but in numerous instances sodium can be applied with advantage. Because the effect of sodium depends on special circumstances and crops, the importance of potassium and sodium changes with the crops. For beet, sodium may almost be deemed an indispensable nutrient element, approaching potassium in importance.

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BOOKS

Annual Review of Biochemistry. Vol. X. Edited by JAMES MURRAY LUCK AND JAMES H. C. SMITH. Annual Reviews, Inc., Stanford University, 1940. Pp. 692. Price, $5.

Another valuable review of the progress of the biochemical sciences. This volume is of special interest to workers in the field of soil science because of chapters dealing with soil and plant deficiencies in relation to animal nutrition; mineral nutrition of plants; nitrogen fixation; and plant growth substances. Other topics covered are oxidations and reductions; enzymes; chemistry of carbohydrates, glycosides, amino acids, and proteins; metabolism of sulfur, carbohydrates, and fats; biochemistry of nucleic acids, purines, pyrimidines, creatine, and creatinine; hormones; vitamins; viohuminescence; metabolism of bacteria; and properties of protein monolayers. References are given to the work of nearly 4000 scientists in these fields.

Colloidal Phenomena. Second Impression, First Edition. By ERNST A. HAUSER. McGraw-Hill Book Company, Inc., New York, 1939. Pp. 294. Price, $3.

Modern viewpoints in colloidal chemistry presented in a very readable and constructive manner. The book is based on notes written by the author for use as a text in regular classes on this subject at the Massachusetts Institute of Technology. The treatment is factual rather than mathematical, but the essential mathematics are included in the appendix.

Conservation of Renewable Natural Resources. By RAPHAEL ZON, WILLIAM S. COOPER, GUSTAF A. PEARSON, HOMER L. SHANTZ, A. E. DOUGLASS, CHARLES G. ABBOT, PAUL B. SEARS, ELLSWORTH HUNTINGTON, MORRIS L. COOKE, SAMUEL T. DANA, MILTON S. EISENHOWER, AND JULIAN F. MCGOWIN. University of Pennsylvania Press, Philadelphia, 1941. Pp. 200. Price, $2.50.

A series of 12 papers presented at the University of Pennsylvania Bicentennial Conference dealing with some fundamental aspects of conservation, particular attention being paid to natural vegetation, climatic factors, and administrative problems. The points of view of the botanist, silviculturist, dendrochronologist, geographer, and soil conservationist are presented in this interesting and instructive volume.

Plant Growth Substances. Second Revised Edition. By HUGH NICOL. Chemical Publishing Co., Inc., Brooklyn, 1941. Pp. 148. Price, $2.

A discussion of the drugs that produce, regulate, or control growth in plants. Of particular interest because of the number of illustrations of applications which are being made in the use of these substances in practical agriculture and horticulture. Chapters on classification, synthesis, and identification of growth substances are included.

Soil Science Society of America Proceedings. Vol. 5. The Soil Science Society of America, G. G. Pohlman, Treas., Morgantown, West Virginia, 1941. Pp. 448. Price, $5.

This volume contains the papers that were presented at the annual meeting of the society held in Chicago, Illinois, December 4–6, 1940. Included among the 77 topics covered in the proceedings are such subjects as Federal-State cooperation; adsorbed ions and plant nutrition; land-use planning; phosphate fixation in soils; clay minerals and base exchange; relation of soil type to quality and composition of plants. A large number of miscellaneous papers dealing with various phases of physics, chemistry, microbiology, fertility, genesis, morphology, and technology as applied to soils are also included. A comprehensive review of the findings of the soil scientists of America for the year, the volume should be available to every worker in this field.

THE EDITORS

FORTY-YEAR STUDIES OF NITROGEN FERTILIZERS[1]

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Results of cylinder studies on the availability of the nitrogen of a number of fertilizer materials, started in 1898 by Voorhees and continued by Lipman and Blair, have been reported periodically in publications from the New Jersey Agricultural Experiment Station (5, 6, 10). The original object of these studies was to compare the effects of the nitrogenous fertilizer materials as measured by yield of dry matter produced, amount of nitrogen in the harvested crops, percentage recovery of the applied nitrogen in the harvested crops, and residual effects on the soil.

The objectives, as originally planned having been attained, the discontinuance of the experiment now seems justifiable. This final paper, therefore, presents a summary of the results of these 40-year studies and includes new data on the effect of the treatments on the status of the exchange-complex of the soil on which the experiments were conducted.

Those familiar with the earlier publications dealing with these experiments will recall that 60 cylinders of soil were involved. These were divided into three groups of 20 cylinders each. The soil of one of these groups received no lime or green manure, that of the second received lime, and that of the third received both lime and green manure. There were 20 different nitrogen treatments, the differences involving either the quantity or quality of the nitrogen materials applied. Penn loam soil was used in the cylinders.

Corn, oats, oats, wheat (or other small grain), and timothy, all heavy consumers of nitrogen, were grown in the cylinders in a 5-year rotation. After each oat crop, corn was grown as a "residual" cover crop, harvested, and removed, but no manure or fertilizer was applied to this crop. In the cylinders receiving lime and green manure, two crops of vetch were grown during each rotation period. The first of these followed the corn crop and the second was between the two oat crops. Accordingly, 16 crops of vetch were grown and worked into the soil of this group of cylinders during the 40-year period. The nitrogen treatments given the soil in each cylinder during the entire 40-year period are shown in table 1.

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[1] Journal Series paper of the New Jersey Agricultural Experiment Station, Rutgers University, department of soil chemistry and microbiology.

[2] Retired.

TABLE 1

Acre rates of application of manures and fertilizers

CYLINDER NUMBER	1898–1922	1923–1938
1	No fertilizer*	Same as 1898–1922
2	No nitrogen	Same as 1898–1922
3	Cow manure, solid, fresh, 16 tons	Same as 1898–1922
4	Cow manure, solid and liquid, fresh	No nitrogen
5	Cow manure, solid, leached	No nitrogen
6	Cow manure, solid and liquid, leached	No nitrogen
7	Nitrate of soda, 160 pounds	Same as 1898–1922
8	Nitrate of soda, 320 pounds	Same as 1898–1922
9	Cow manure, solid, fresh; nitrate of soda, 160 pounds	Same as 1898–1922
10	Cow manure, solid, fresh; nitrate of soda, 320 pounds	Same as 1898–1922
11	Cow manure, solid and liquid, fresh; nitrate of soda, 160 pounds	Nitrate of soda, 160 pounds
12	Cow manure, solid and liquid, fresh; nitrate of soda, 320 pounds	Nitrate of soda, 320 pounds
13	Cow manure, solid, leached; nitrate of soda, 160 pounds	Nitrate of soda and sulfate of ammonia, equivalent to 320 pounds nitrate of soda
14	Cow manure, solid, leached; nitrate of soda, 320 pounds	Nitrate of soda, 320 pounds
15	Cow manure, solid and liquid, leached; nitrate of soda, 160 pounds	Nitrate of soda, 320 pounds
16	Cow manure, solid and liquid, leached; nitrate of soda, 320 pounds	Nitrate of soda and sulfate of ammonia equivalent to 320 pounds of nitrate of soda
17	Sulfate of ammonia, equivalent to 320 pounds nitrate of soda	Same as 1898–1922
18	Dried blood, equivalent to 320 pounds nitrate of soda	Same as 1898–1922
19	Cow manure, solid, leached; sulfate of ammonia, equivalent to 320 pounds of nitrate of soda	Sulfate of ammonia equivalent to 320 pounds of nitrate of soda
20	Cow manure, solid, leached; dried blood, equivalent to 320 pounds of nitrate of soda	Dried blood, equivalent to 320 pounds of nitrate of soda

* All cylinders, except no. 1, received superphosphate and muriate of potash at the rate of 640 pounds of the former and 320 pounds of the latter, per acre annually.

CROP YIELDS AND NITROGEN RECOVERIES

The summarized data, showing total yields of dry matter, nitrogen recoveries, and percentages of nitrogen in the harvested crops, are recorded in table 2.

TABLE 2

Total yields of dry matter and nitrogen contents of crops for 40 years

CYLINDER NUMBER	FORM OF NITROGEN APPLIED*	TOTAL NITROGEN APPLIED	YIELD OF DRY MATTER			TOTAL NITROGEN IN CROPS			AVERAGE NITROGEN IN CROPS		
			Unlimed	Limed	Lime and green manure	Unlimed	Limed	Lime and green manure	Unlimed	Limed	Lime and green manure
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	per cent	per cent	per cent
1	No fertilizer	0.00	1,166	3,275	3,726	15.94	34.83	40.88	1.37	1.06	1.10
2	No nitrogen	0.00	3,400	4,193	5,440	25.62	40.12	53.74	0.75	0.96	0.99
3	Manure	160.22	7,646	8,633	9,458	74.96	80.49	95.77	0.98	0.93	1.01
4	Manure	102.76	6,695	8,776	9,547	64.74	79.99	94.61	0.97	0.91	0.99
5	Manure	98.25	6,284	7,754	9,133	61.59	72.97	91.94	0.98	0.94	1.00
6	Manure	102.17	6,535	8,360	9,257	64.57	80.11	94.34	0.99	0.96	1.02
7	Sodium nitrate	30.85	3,422	6,611	8,065	34.56	57.71	81.07	1.01	0.87	1.01
8	Sodium nitrate	61.71	4,368	8,505	9,232	44.44	76.22	90.63	1.02	0.90	0.98
9	Manure and nitrate	191.97	8,727	10,316	11,294	85.37	100.94	115.90	0.98	0.98	1.03
10	Manure and nitrate	221.98	10,202	11,675	12,198	104.31	116.36	130.26	1.02	1.00	1.07
11	Manure and nitrate	135.08	7,806	10,598	10,906	82.22	107.01	112.76	1.05	1.00	1.03
12	Manure and nitrate	164.52	8,573	11,195	12,615	91.67	113.59	138.54	1.07	1.01	1.10
13	Manure, nitrate, sulfate	141.50	7,781	10,046	10,342	77.49	96.94	107.07	1.00	0.96	1.04
14	Manure and nitrate	160.01	8,768	10,666	11,264	89.80	103.51	119.13	1.02	0.97	1.06
15	Manure and nitrate	145.42	8,063	10,081	11,080	81.67	99.71	114.53	1.01	0.99	1.03
16	Manure, nitrate, sulfate	163.93	8,849	10,799	11,543	93.30	108.78	119.62	1.05	1.01	1.04
17	Ammonium sulfate	62.81	2,942	7,012	7,552	31.98	64.72	74.05	1.09	0.92	0.98
18	Dried blood	62.52	3,580	6,147	7,312	40.25	63.48	78.19	1.12	1.03	1.07
19	Manure and sulfate	160.99	6,837	9,471	10,171	75.40	97.05	105.47	1.10	1.02	1.04
20	Manure and blood	160.79	7,095	9,609	10,546	77.78	97.51	111.27	1.10	1.01	1.06
	Average............		6,437	8,686	9,534	65.88	84.60	98.49	1.03	0.98	1.03

* For more details on manure and fertilizer treatments, see table 1.

Yields of dry matter produced

The highest crop yields were obtained when the manure and fertilizers were supplemented by lime and green-manure treatments. If the average crop yield of the cylinders under these supplemental treatments is rated at 100, that of the cylinders receiving lime without green manure would be 91, and that of the cylinders receiving neither would be 68.

The increases in crop yields resulting from the use of nitrogen were closely correlated with the quantities of nitrogen applied. The highest yields were produced by the use of manure plus nitrate of soda.

No matter what the system of soil management, the crop yields, per unit of nitrogen supplied, were always greater from the use of nitrate of soda than from the use of manure, sulfate of ammonia, or dried blood.

Nitrogen recoveries in harvested crops

The highest nitrogen recoveries were obtained when the manure and fertilizers were supplemented with lime and green-manure treatments. If the average nitrogen recovery in the crops of the cylinders under these supplemental treatments is rated at 100, that of the crops in the cylinders receiving lime without green manures would be 86, and that of the crops in the cylinders receiving neither would be 67.

More nitrogen was recovered in the harvested crops than was applied, when this element was supplied in the form of nitrate of soda, sulfate of ammonia, or dried blood, except from the cylinders in which no lime had been used. When manure was the only source of nitrogen applied, the amount of nitrogen recovered was always less than that which the manure supplied.

No matter what the system of soil management, the nitrogen recoveries, per unit of nitrogen supplied, were always greater from the use of nitrate of soda than from the use of manure, sulfate of ammonia, or dried blood.

Percentages of nitrogen in harvested crops

The nitrogen contained in the harvested crop averaged close to 1 per cent of the weight of dry matter. The extremes were 0.75 and 1.37 per cent, both of which were found in crops that had been grown without the use of lime and green manures. The lower percentage was that in crops receiving no nitrogen; and the higher, in crops receiving no nitrogen, phosphate, or potash fertilizers.

With only two exceptions, the use of lime without green manure resulted in lowering the percentage of nitrogen in the harvested crops. The average amount of nitrogen in the crops was 0.98 per cent for the limed cylinders, as compared with 1.03 per cent for the cylinders receiving lime and green manure and those receiving neither.

Of the fertilized crops, the highest percentage of nitrogen tended to be found in those which had received sulfate of ammonia or dried blood and which had been grown without the supplemental use of lime and green manure.

TABLE 3
Nitrogen balance sheet after 40 years*

CYLINDER NUMBER	FORM OF NITROGEN APPLIED‡	IN FERTILIZERS + RAIN WATER‡	TOTAL IN SOIL, RAIN, AND FERTILIZERS‡	RECOVERED IN CROPS			IN SOIL			TOTAL RECOVERED IN CROPS AND SOIL			PERCENTAGE RECOVERED IN CROPS AND SOIL		
				Unlimed	Limed	Lime and green manure	Unlimed	Limed	Lime and green manure	Unlimed	Limed	Lime and green manure	Unlimed	Limed	Lime and green manure
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.			
1	No fertilizer	6.22	161.69	15.94	34.83	40.88	77.86	81.83	92.96	93.80	116.66	133.84	58.0	72.2	82.8
2	No nitrogen	6.22	161.69	25.62	40.12	53.74	69.12	77.86	100.90	94.74	117.98	154.64	58.6	73.0	95.6
3	Manure	166.44	321.91	74.96	80.49	95.77	131.89	148.57	170.82§	206.85	229.06	266.59	64.3	71.2	82.8
4	Manure	108.98	264.45	64.74	79.99	94.61	86.60	100.90	124.74	151.34	180.89	219.35	57.2	68.4	82.9
5	Manure	104.47	259.94	61.59	72.97	91.94	100.10	109.64	129.50	161.69	182.61	221.44	62.2	70.3	70.3
6	Manure	108.39	263.86	64.57	80.11	94.34	107.26	116.79	132.68	171.83	196.90	227.02	65.1	74.6	86.0
7	Sodium nitrate	37.07	192.54	34.56	57.71	81.07	89.78	88.98	113.61	124.34	146.69	194.68	64.6	76.2	101.1
8	Sodium nitrate	67.93	223.40	44.44	76.22	90.63	82.63	88.19	112.02	127.07	164.41	202.65	56.9	73.6	90.7
9	Manure and nitrate	198.19	353.66	85.37	100.94	115.90	151.75	146.19	170.82§	237.12	247.13	286.72	67.0	69.9	81.1
10	Manure and nitrate	228.20	383.67	104.31	116.36	130.26	159.69§	140.63	167.64§	264.00	256.99	297.90	68.8	67.0	77.6
11	Manure and nitrate	141.30	296.77	82.22	107.01	112.76	91.37	111.23	129.50	174.19	218.24	242.26	58.7	73.5	81.6
12	Manure and nitrate	170.74	326.21	91.67	113.59	138.54	97.72	118.38	134.27	189.39	231.97	272.81	58.1	71.1	83.6
13	Manure, nitrate, sulfate	147.72	303.19	77.49	96.94	107.07	104.08	131.09	146.19	181.57	228.03	253.26	59.9	75.2	83.5
14	Manure and nitrate	166.23	321.70	89.80	103.51	119.13	111.23	129.50	144.60	201.03	233.01	263.73	62.5	72.4	82.0
15	Manure and nitrate	151.64	307.11	81.67	99.71	114.53	116.79	128.71	133.48	198.46	228.42	248.01	64.6	74.4	80.8
16	Manure, nitrate, sulfate	170.15	325.62	93.30	108.78	119.62	97.72	131.89	146.98	191.02	240.67	266.60	58.7	73.9	81.9
17	Ammonium sulfate	69.03	224.50	31.98	64.72	74.05	77.06	103.28	130.30	109.04	168.00	204.35	48.6	74.8	91.0
18	Dried blood	68.74	224.21	40.25	63.48	78.19	73.89	108.85	116.79	114.14	172.33	194.98	50.9	76.9	87.0
19	Manure and sulfate	167.21	322.68	75.40	97.05	105.47	94.54	135.86	145.39	169.94	232.91	250.86	52.7	72.2	77.7
20	Manure and blood	167.01	322.48	77.78	97.51	111.27	88.98	120.76	149.37	166.76	218.27	260.64	51.7	67.7	80.8
Average				65.88	84.60	98.49	100.50	115.96	134.63	166.38	200.56	233.12	59.5	72.4	84.0

* In 175 pounds of soil to a depth of 6¾ inches.

† For specific nitrogen treatments see table 1. Nitrogen in original soil of each cylinder 155.47 gm.

‡ Rain supplied 6.22 gm. (estimated) in 40 years.

§ More nitrogen in soil than at start of experiment.

Nitrogen balance after 40 years

The nitrogen in the harvested crops had its origin partly in the organic matter originally contained in the soil and, in the case of the lime and green-manure groups, in that supplied by the 16 vetch crops, and partly in the manure and fertilizers which were applied to the soil. In order to determine the nitrogen balance after the 40-year period, it becomes necessary to consider not only the quantities of nitrogen added to the soil during this period, but the amount of nitrogen finally contained in the soil of each of the several cylinders, as compared to that in the original soil. Such a balance sheet is shown in table 3. The following significant facts are to be noted:

Except for 4 of the 60 cylinders, the soil contained less nitrogen after the 40-year period than it did originally. In these four exceptions, the soil received annual applications of manure at the rate of 16 tons per acre; and in three of these four, supplemental lime and green-manure treatments.

After 40 years, the average nitrogen content of the soil in the cylinders receiving lime and green manure, lime without green manure, and neither lime nor green manure, was 87, 75, and 65 per cent, respectively, of that originally present in the soil.

Taking into consideration the nitrogen content of the soil at the beginning and end of the 40-year period, in only 1 of the 60 cylinders was as much nitrogen recovered in the crop as the fertilizer and soil supplied. That cylinder received nitrogen in the form of nitrate of soda, applied at the rate of 160 pounds per acre annually during the entire 40 years, and supplemental treatments of lime and green manure.

There was very little difference in the percentage recovery of nitrogen from soil plus commercial fertilizer, no matter whether the nitrogen was supplied in the form of nitrate of soda, sulfate of ammonia, or dried blood.

The nitrogen content of the soil at the end of the 40-year period was lower in the cylinders receiving nitrate of soda than in those receiving an equal amount of nitrogen as dried blood or sulfate of ammonia, except in the unlimed series.

ORGANIC MATTER BALANCE AFTER 40 YEARS

The organic matter balance in the soil at the end of the 40-year period is shown in table 4. The following points are significant:

The organic matter content of the soil was not maintained, on the average, under any one of the three systems of soil management employed. The loss of organic matter was least under the lime and green-manure system, and most where neither lime nor green manure was used.

Only when manure was applied at the rate of 16 tons per acre annually and where the lime and green-manure system of soil management was employed, was the organic matter content of the soil always increased (1).

PRESENT STATUS OF EXCHANGE COMPLEX OF SOIL

A sample of soil, to a depth of 6⅔ inches, was taken from each cylinder at the end of the 40-year period. These samples were prepared and examined by the usual procedure for pH, cation-exchange capacity, exchangeable cations, and electrodialyzable anions (7, 8). The data obtained from these determinations are recorded in table 5 and in figures 1 and 2.

In figure 1, the cation-exchange capacity and exchange hydrogen are graphically shown, in terms of milliequivalents per 100 gm. of soil, for each different source of nitrogen used since 1923, under the three soil management systems employed. The percentage-unsaturation values of these soils are also graphically shown.

In figure 2, the exchangeable calcium, magnesium, and potassium are graphically shown, in terms of milliequivalents per 100 gm. of soil, for each different source of nitrogen used since 1923, under the three soil management systems employed.

TABLE 4
Organic matter* balance after 40 years

TREATMENT	1898	1938	GAIN OR LOSS
Unlimed	78,800	50,800	−28,000
Limed	78,800	58,400	−20,400
Lime and green manure	78,800	67,600	−11,200
Lime and green manure plus manure†	78,800	86,050	+7,250

* Nitrogen (pounds per acre) × 20.

† Average of three cylinders (nos. 3, 9, 10) on which fresh manure was applied annually at the rate of 16 tons per acre in the series of cylinders under the lime and green-manure system of soil management.

Cation-exchange capacity and exchangeable cations

The average exchange capacity of the soil in the cylinders under the lime and green-manure system was 14.8 milliequivalents per 100 gm. of soil, whereas that of the soil in the cylinders receiving lime without green manure was 13.5 milliequivalents, and that of the soil receiving neither was 11.5 milliequivalents. The higher exchange capacity of the soil under the lime and green-manure system was correlated with the higher humus content of the soil under that system of management.

The cation-exchange capacity of the soil was always highest when the nitrogen was supplied in the form of manure (8). As was to be expected, nitrate of soda, sulfate of ammonia, and dried blood produced no significant effects on the exchange capacity of the soil.

Exchange hydrogen and pH. It is apparent from the data in table 5 that no relation exists between the pH values obtained and the content of ex-

changeable hydrogen in the soil. For example, the soil of the lime and green-manure group had a lower pH value than that of the group receiving lime without green manure, but it contained less exchange hydrogen. Conversely, the content of exchangeable bases was higher in the soil of the lime and green-manure section. This difference in behavior is no doubt due to the fact that
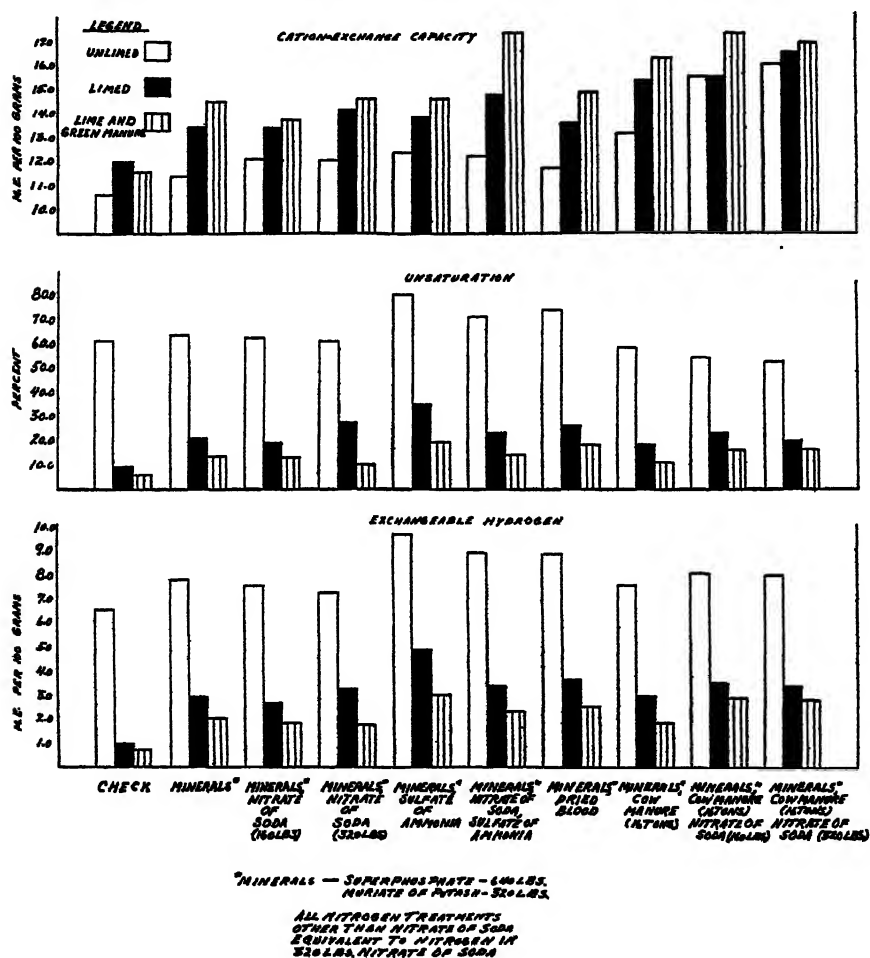
FIG. 1. RELATION BETWEEN NITROGEN SOURCES, CATION-EXCHANGE CAPACITY, UNSATURATION, AND EXCHANGEABLE HYDROGEN OF PENN LOAM

the exchange complex of the soil of this latter group of cylinders contains more organic exchange material.

That the continuous use of ammonium sulfate, without lime, has depleted the exchange complex of bases is indicated by the fact that the exchangeable hydrogen content of the soils so treated was relatively high. Under the more

practical soil-management systems, involving the use of lime and green manure, this effect of ammonium sulfate in increasing the amount of exchangeable hydrogen has been largely corrected.

Exchangeable calcium and magnesium. In general, the exchangeable calcium content of the soil under the lime and green-manure system was somewhat
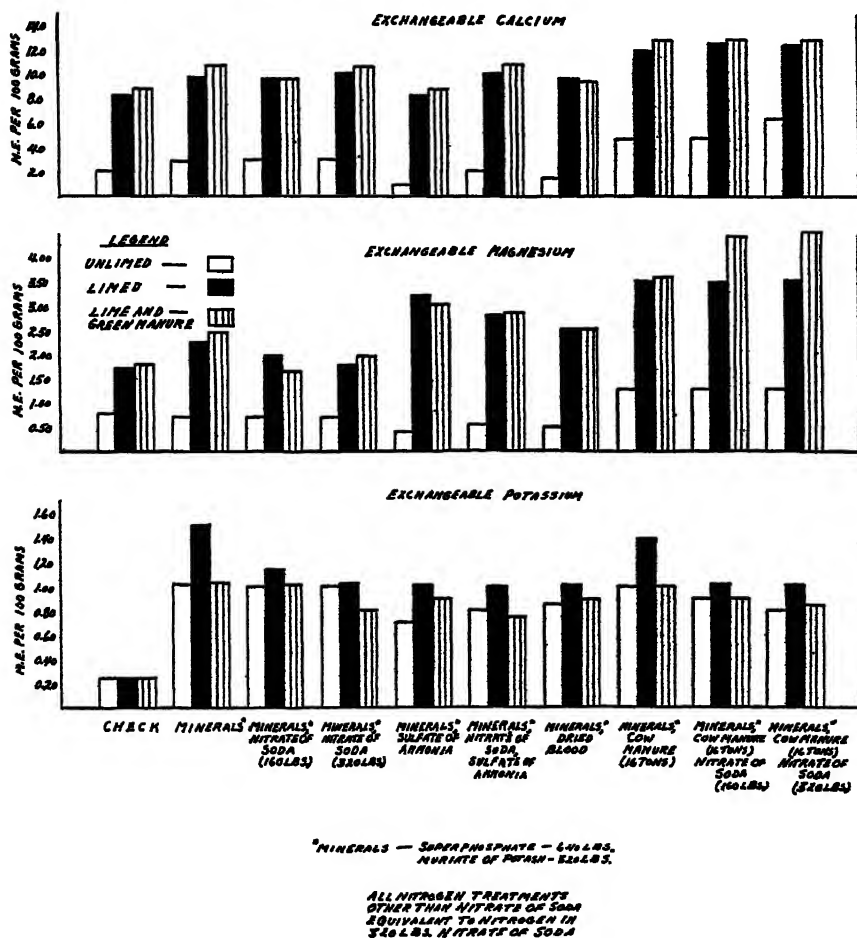
FIG. 2. RELATION BETWEEN NITROGEN SOURCES AND EXCHANGEABLE CALCIUM, MAGNESIUM, AND POTASSIUM OF PENN LOAM

greater than that of the soil under the system employing lime without green manure. The average content of exchangeable calcium amounted to approximately 10.5 milliequivalents per 100 gm. of soil for the lime and green-manure section, and only 10 milliequivalents for the section which was limed but on which green manure was omitted. In spite of the fact that greater yields

TABLE 5

Effects of 40-year fertilizer treatments on Penn loam soil

Values are given for three field treatments of each plot: **Unlimed (U)**, **Limed (L)**, and **Lime and green manure (LG)**. Unless noted, values are in m.e./100. Unsaturation is in per cent. "T" = trace.

Cylinder number	Treatment[a]	pH U	pH L	pH LG	CEC U	CEC L	CEC LG	Unsat. U	Unsat. L	Unsat. LG	H U	H L	H LG	Ca U	Ca L	Ca LG	Mg U	Mg L	Mg LG	K U	K L	K LG	Na U	Na L	Na LG	Total anions U	Total anions L	Total anions LG	PO₄ U	PO₄ L	PO₄ LG	SO₄ U	SO₄ L	SO₄ LG
1	No fertilizer	4.90	6.65	6.45	10.6	12.0	11.6	61.3	8.3	6.0	6.50	1.00	0.70	2.05	8.35	8.75	1.75	2.15	1.75	0.25	0.25	0.15	T	0.25	0.25	0.75	1.50	1.80	1.80	2.70	3.10	0.40	0.20	0.45
2	No nitrogen	5.10	6.70	6.30	10.3	12.2	13.7	53.4	10.2	10.2	5.50	1.40	1.40	3.10	9.30	9.65	1.00	1.90	1.65	0.40	1.05	1.00	0.15	0.15	0.10	2.20	3.45	4.20	1.80	3.45	3.45	0.20	0.20	0.40
3	Manure	4.95	6.20	6.10	13.2	15.4	16.2	56.8	18.8	10.8	7.50	2.90	1.75	2.45	11.05	12.75	1.30	2.75	3.01	1.00	1.55	1.00	0.25	0.20	0.25	2.65	4.55	5.25	2.30	4.20	4.75	0.35	0.35	0.45
4	Manure	4.90	6.40	6.00	11.5	12.9	14.4	73.9	24.0	12.8	8.50	3.10	1.85	2.45	9.40	10.70	0.60	2.30	2.30	1.05	1.40	1.15	0.10	0.05	0.20	2.60	4.00	5.30	2.30	3.65	5.30	0.30	0.30	0.40
5	Manure	4.90	6.30	6.05	11.3	14.0	15.1	51.9	28.6	14.9	7.00	4.00	2.25	2.95	9.30	11.20	0.60	2.35	2.51	1.00	1.40	1.15	0.10	0.10	0.20	2.65	4.40	5.25	2.30	4.15	5.30	0.25	0.20	0.40
6	Manure	4.85	6.40	6.20	12.6	14.4	14.9	55.0	22.2	14.8	8.20	3.20	2.25	2.90	11.25	11.05	0.70	2.70	2.75	0.95	1.50	1.05	0.25	0.20	0.10	2.50	4.80	4.90	2.20	3.90	3.70	0.25	0.25	0.30
7	Sodium nitrate	5.10	6.50	6.40	13.4	13.6	13.6	55.5	14.9	12.8	7.00	2.00	1.75	3.45	9.80	9.60	0.70	1.70	1.85	0.95	1.30	1.15	0.25	0.25	0.25	3.00	3.40	3.05	2.60	2.80	2.60	0.20	0.20	0.30
8	Sodium nitrate	5.20	6.55	6.30	11.4	12.7	13.5	57.0	22.0	12.9	6.50	2.80	1.75	3.30	9.00	9.40	0.85	1.50	1.75	0.90	1.15	1.15	0.30	0.10	0.10	3.00	3.05	3.35	2.35	3.05	3.65	0.20	0.20	0.35
9	Manure and nitrate	4.80	6.30	6.10	15.1	15.1	16.4	53.0	23.1	16.3	8.00	3.50	2.75	4.80	11.55	12.75	1.50	2.45	2.55	0.85	1.30	1.20	0.25	0.25	0.30	3.62	3.65	3.55	2.45	3.35	3.55	0.30	0.25	0.35
10	Manure and nitrate	4.95	6.25	6.00	15.5	16.0	16.4	51.6	20.0	16.7	8.00	3.20	2.75	6.25	12.40	12.75	1.35	3.70	4.35	1.05	1.90	0.85	0.30	0.25	0.30	3.10	4.15	4.55	2.20	3.55	4.40	0.55	0.25	0.35
11	Manure and nitrate	4.80	6.45	6.15	11.6	13.3	13.5	71.1	24.0	13.3	8.25	3.20	1.80	2.40	9.40	9.65	0.70	2.15	1.90	0.90	1.05	1.05	0.30	0.20	0.30	2.65	4.30	3.10	2.20	3.10	3.20	0.30	0.25	0.30
12	Manure and nitrate	5.00	6.50	6.25	12.3	14.1	15.1	63.0	21.2	10.5	7.75	3.00	1.60	2.70	10.10	10.25	0.65	2.30	2.15	0.95	1.20	1.05	0.30	0.15	0.35	2.75	3.95	2.80	2.45	3.10	2.80	0.30	0.35	0.35
13	Manure, nitrate, sulfate	4.55	6.25	6.10	12.6	14.6	16.3	71.4	20.5	12.9	9.00	3.00	2.10	2.10	10.00	11.45	0.80	2.80	3.90	0.80	1.35	1.20	0.15	0.15	0.20	2.80	4.00	3.90	2.40	3.95	3.10	0.40	0.30	0.35
14	Manure and nitrate	5.00	6.50	6.20	13.0	15.1	15.7	59.6	23.1	9.5	7.75	3.50	1.50	3.35	11.10	11.55	0.70	1.85	2.00	0.70	1.20	0.95	0.40	0.30	0.40	3.15	4.65	3.10	2.75	3.90	3.65	0.25	0.25	0.40
15	Manure and nitrate	5.15	6.40	6.20	12.6	14.5	15.0	61.5	23.3	10.0	7.75	3.50	1.50	3.30	10.15	10.65	0.70	1.85	2.00	1.20	1.20	1.05	0.30	0.30	0.30	3.05	4.20	2.75	2.75	3.10	3.90	0.30	0.30	0.40
16	Manure, nitrate, sulfate	4.70	6.25	5.90	12.1	14.8	16.3	70.2	25.6	15.3	8.50	3.80	2.50	2.10	10.20	10.10	0.55	2.55	2.50	0.80	1.30	1.00	0.20	0.20	0.30	3.10	4.65	3.70	2.50	3.10	3.70	0.40	0.40	0.40
17	Ammonium sulfate	4.10	5.70	5.80	11.6	13.0	14.1	83.0	32.3	19.8	9.20	4.20	2.80	0.85	9.60	8.50	0.50	3.35	2.55	0.95	1.30	0.95	0.10	0.10	0.20	2.00	4.35	4.20	2.10	3.05	2.75	0.40	0.60	0.50
18	Dried blood	4.40	6.30	5.95	12.7	14.3	13.8	75.4	28.7	18.1	8.75	3.80	2.50	1.75	8.40	8.85	0.50	2.45	2.55	1.30	0.95	0.95	0.10	0.10	0.10	2.00	4.10	3.95	2.60	3.35	3.00	0.45	0.45	0.50
19	Manure and sulfate	4.10	5.65	5.60	12.7	14.2	15.2	78.7	31.4	19.7	10.00	4.50	3.00	0.95	8.40	9.35	0.45	3.05	3.65	0.90	0.70	0.90	0.10	0.10	0.10	2.30	4.60	4.65	1.65	3.70	3.55	0.55	0.45	0.55
20	Manure and blood	4.50	6.20	5.90	12.1	14.1	15.7	73.2	24.1	16.1	8.75	3.40	2.50	1.55	10.15	10.55	0.45	2.75	2.65	0.75	0.90	0.75	0.15	0.10	0.10	2.45	4.65	4.65	1.55	3.80	4.00	0.25	0.30	0.30
	Average				11.5	13.5	14.8	63.6	20.0	13.7	7.92	3.15	2.05	2.85	9.97	10.47	0.74	2.50	2.60	0.89	1.17	0.90	0.21	0.15	0.31	2.88	4.40	4.71	2.26	3.40	3.38	0.30	0.30	0.38

[a] For more details on manure and fertilizer treatments, see table 1.

were obtained from the soil of the lime and green-manure section, there is apparently a conservation of exchangeable calcium under this system. This may be due to the influence of the green manure in storing bases in its tissues and subsequently returning them to the soil, and to the stabilizing influence of the organic exchange complex on calcium.

The exchangeable calcium content of the soil from the cylinders receiving manure was invariably higher than was that of the soil in the cylinders receiving any other form of nitrogen, irrespective of the soil management system employed. Evidently the manure carried additional calcium which was exchangeable, and the higher exchange capacity of the manured soils reduced the loss of calcium by leaching. The use of ammonium sulfate caused a reduction in the amount of the exchangeable calcium, as was to be expected.

The data for the exchangeable magnesium were of the same order as those for exchangeable calcium, with the exception that the exchange complex of the limed and green-manured soil which received ammonium sulfate contained larger amounts of magnesium than did the exchange complex of the soil receiving nitrate of soda or dried blood. This is apparent from figure 2.

Exchangeable potassium. Although the potash applications were the same on all cylinders (except for the check, which was untreated), the content of exchangeable potassium was slightly higher in the soil which was limed but not green manured than in that receiving both lime and green manure. This difference may have been due to a greater production of dry matter under the lime and green-manure system, and the resulting greater removal of exchangeable potassium from the soil.

The nitrogen fertilizer materials, whether organic or inorganic, had no apparent effect on the amount of exchangeable potassium in the soil. Contrary to the findings for exchangeable calcium and magnesium, there was no increase in exchangeable potassium in the complex of the soils of the manured cylinders.

Exchangeable sodium. In all cases, the amount of exchangeable sodium was low, varying from 0.1 to 0.45 milliequivalents per 100 gm. of soil. It is interesting to note, however, that although the exchangeable sodium was somewhat higher in the soil receiving annual applications of nitrate of soda for 40 years than on the others, even in this case only 2 or 3 per cent of the exchange complex was satisfied by sodium. This amount of sodium was not sufficient to cause any objectionable physical effects on the soil.

Residual effect of manure

In table 6 the pounds of exchangeable cations and of phosphorus per 2,000-000 pounds of soil are reported for the cylinders receiving manure annually for 40 years, for those receiving manure for the first 24 of the 40 years, and for those receiving only superphosphate and muriate of potash. The following significant fact is to be noted:

Manure has a marked residual effect, which is shown by its holding the

cation-exchange capacity of the soil at a high level for 16 years after the manure treatments were discontinued. The cation exchange capacity of the manured soil, expressed in terms of calcium, was still between 500 and 600 pounds higher per acre, to plow depth, than was that of the soil receiving no manure. The manured soil likewise showed a higher retention of calcium, magnesium, and phosphorus.

Electrodialyzable anions

The determination of electrodialyzable anions was carried out on the soils in order to study the influence of the three soil-management systems on the availability of the phosphorus, and to determine whether the continuous use of ammonium sulfate had resulted in an accumulation of sulfate ions.

TABLE 6

Residual effects of manure on the soil exchange complex
Results in pounds per 2,000,000 of soil

CYLINDER NUMBER	TREATMENT	CATION-EXCHANGE CAPACITY*			EXCHANGEABLE CATIONS														ELECTRO-DIALYZABLE PHOSPHATES		
					H			Ca			Mg			K			Na			P		
		Unlimed	Limed	Lime and green manure	Unlimed	Limed	Lime and green manure	Unlimed	Limed	Lime and green manure	Unlimed	Limed	Lime and green manure	Unlimed	Limed	Lime and green manure	Unlimed	Limed	Lime and green manure	Unlimed	Limed	Lime and green manure
3	Cow manure 40 years	5295	6175	6500	152	59	35	1865	4790	5110	316	876	900	780	1095	820	69	92	115	2265	2945	3290
4, 5, 6	Cow manure 24 years, no N for next 16 years	4730	5535	5935	160	69	43	1110	4010	4410	146	596	627	780	1150	875	55	37	105	1410	2390	2360
2	Superphosphate and muriate of potash only	4130	4890	5495	111	28	28	1245	3730	3870	243	401	462	820	1210	860	69	46	115	1120	1675	1920

* Calculated to terms of Ca; conversion factors (m.e. per 100 gm. soil to pounds per acre): H = 20.2, Ca = 401.0, Mg = 243.2, K = 782.0, Na = 460.0, P = 620.0.

The electrodialyzable anions in the soil consisted mainly of inorganic acids (phosphoric, sulfuric, nitric, and hydrochloric), with smaller amounts of organic acids. The total amount of inorganic acids far exceeded that of the organic acids. Thus, the combined phosphates and sulfates made up between 80 and 90 per cent of the total titrable anions in the soil. Of this, phosphoric acid comprised about 90 per cent and sulfuric acid the remaining 10 per cent (9).

The data for the combined anions indicated, in general, that the soils which had been treated with lime and green manure contained the most electrodialyzable anions, followed by those receiving lime without green manure, and those receiving neither. This may be explained by the fact that phosphates, in the presence of lime, form tricalcium phosphates (4), which are

easily electrodialyzed (2), and also by the fact that this limed and green-manured soil contained more dialyzable organic acids. This supposition is confirmed by the results obtained on the soils receiving manure, in which the content of electrodialyzable anions was considerably higher than it was in those receiving only inorganic forms of nitrogen.

Electrodialyzable phosphate. The average electrodialyzable phosphate content of the soil receiving lime and green manure and lime without green manure was in excess of that of the unlimed soils. It is a recognized fact that added phosphate, in the presence of exchangeable calcium, and at pH values above 5.8 (as found in the limed soil), form tricalcium phosphate, which is readily electrodialyzable, whereas under more acid conditions (pH values less that 5.8), iron and aluminum phosphates are formed which are not readily electrodialyzable (2, 4). Thus, under the lime and the lime and green-manure systems of soil management, the phosphates were more available than where neither lime nor green manure was employed.

On the other hand, the soil that was regularly treated with nitrate of soda was consistently lower in electrodialyzable phosphate than was that of the other nitrogen-treated cylinders. It will be recalled that the nitrogen recovery in the crops was greatest from the cylinders receiving nitrate of soda, and it is possible that, under these conditions, more phosphorus was made available and was utilized by the crop, and less of it remained in the soil (3).

The continuous use of sulfate of ammonia reduced the amount of electrodialyzable phosphate, irrespective of the system of soil management employed. Under the acid conditions thus produced in the soil, phosphorus was fixed largely as iron and aluminum phosphates.

Electrodialyzable sulfates. In nearly every case where ammonium sulfate was used as the source of nitrogen, the quantity of electrodialyzable sulfates in the soil was higher than otherwise, irrespective of the system of soil management employed. This was to be expected. In no case was the accumulation of sulfate ions greater than 5 per cent of the total amount of sulfate added over the period of 40 years.

SUMMARY

This is a final statement on a 40-year study of the comparative effects of various carriers of nitrogen on crop growth and nitrogen recovery, and on the status of the exchange complex of the Penn loam soil on which the test was conducted. The comparisons were made under three systems of soil management, viz; with lime and green manure; with lime in the absence of green manure; and with neither lime nor green manure.

In considering these data it is necessary to keep in mind that each nitrogen material was tested separately. Thus, the nitrate-treated soil never received any sulfate of ammonia or dried blood. Furthermore, the cropping system employed was one which was designed to exhaust the soil of nitrogen, legumes being omitted from the rotation. However, 16 crops of vetch were grown and

worked into the soil under the lime and green-manure system of soil management.

The most significant facts developed were as follows:

The crop yields under the lime and green-manure system of soil management were 9 per cent higher than those produced without the use of green manure, and 32 per cent higher than those produced with neither lime nor green manure.

Nitrate of soda was the most effective carrier of nitrogen employed, the average crop yields being greater from the use of this material, per unit of nitrogen applied, than from any other form of nitrogen.

Nitrogen recoveries in the harvested crops under the lime and green-manure system of soil management averaged 14 per cent greater than those obtained without the use of green manure, and 33 per cent greater than those obtained with neither lime nor green manure.

The nitrogen recovery in the harvested crops, per unit of nitrogen applied, always averaged greater from the cylinders receiving nitrate of soda than from those receiving any other form of nitrogen.

Except for the cylinders receiving 16 tons of manure per acre annually, the soil contained less nitrogen at the end of the 40-year period than at the beginning.

The nitrogen losses from the soil averaged 13 per cent under the lime and green-manure system of soil management, 25 per cent when the green manure was omitted, and 35 per cent when neither lime nor green manure was employed.

In only one cylinder—that receiving nitrate of soda at the rate of 160 pounds per acre—was as much nitrogen recovered in the crop as the fertilizer and soil supplied.

The soil receiving nitrate of soda contained less nitrogen, at the end of the 40-year period, than the soil receiving any other form of nitrogen, both under the lime and green-manure and the lime without green-manure systems of soil management.

The organic-matter content of the soil was dependably maintained and increased only when manure was applied at the rate of 16 tons per acre annually, and when the soil-management system included the use both of lime and green manure.

The residual effects of manure were definitely shown, 16 years after the manure treatments were discontinued, by the higher cation-exchange capacity of the soil, and by its higher retention of calcium, magnesium, and phosphorus.

The exchangeable calcium content of the soil was highest under the lime and green-manure system of soil management.

The exchangeable potassium content of the soil was highest where lime had been used without green manure.

Only 2 to 3 per cent of the exchange complex of the soil was satisfied by sodium as a result of the heaviest applications of nitrate of soda.

Soil which had been limed and green manured contained larger amounts of electrodialyzable anions than that which had not been so managed.

Soil regularly treated with nitrate of soda was consistently lower in electrodialyzable phosphates than that not so treated.

Soil that had been treated with sulfate of ammonia contained the largest amounts of electrodialyzable sulfate ions, but the highest recovery was not more than 5 per cent of the total amount applied.

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REPLACEMENT OF ADSORBED PHOSPHATE FROM KAOLINITE BY FLUORIDE[1]

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One of the main problems of the soil chemist is the determination of the nutrients present in the soil which are of significance for plant growth. These have been commonly called the "available" nutrients. Since the time of Daubeny (4) many methods have presumed to measure the quantity of an "available" nutrient present in a given soil. The excretion of CO_2 by plant roots was used as a "reason" to justify the selection of a weak or dilute acid as a nutrient extractant, and it was further assumed that a solution which simulated the dissolving action of a plant root would lead to the most satisfactory chemical method for evaluating the "available" nutrients of a soil. One of us (3) previously pointed out the fallacies of this assumption and emphasized the importance of determining all, or a known proportional part, of a nutrient form or forms of a given element in the soil when a chemical determination is made. This viewpoint considers the nutrients in the soil in terms of their chemical form or structure and advocates chemical methods that will determine the amount of a specific form of an element which is present in the soil.

Chemical methods of distinguishing soil phosphates have been difficult to develop because of the comparatively large numbers of forms of phosphates in soils. A few of the inorganic forms are water-soluble phosphate, calcium phosphates of varying solubilities, iron and aluminum phosphates, and adsorbed or replaceable phosphate. A plant may obtain part of its phosphorus from each of these forms to a varying degree throughout a growing season. There is no *a priori* reason to expect an extracting solution to remove the same proportion of these phosphates as will be utilized by a crop. A more productive approach and one which has already resulted in practical potash fertilizer recommendations in Illinois (2) suggests that each chemical test should measure quantitatively the amount of a nutrient-form of an element in the soil. A large number of these values can then be correlated with the growth of a given crop and a field calibration established. This investigation is an attempt to apply the general principle expressed above, to the question of phosphate fertility in Illinois soils.

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[1] Contribution from the department of agronomy, University of Illinois. Published with the approval of the director of the experiment station.

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The question of chemical form is included in phosphate fractionation studies such as those of Dean (6) and of Fisher and Thomas (9). The latter workers attempted a separation on the basis of rate of solubility in buffered acids at two pH ranges. Truog and Dean (26) have suggested successive extractions with dilute sulfuric acid to distinguish between calcium phosphates and iron and aluminum phosphates.

Phosphate fractionation studies stand in close relationship to those of phosphate "fixation." Both Murphy (17) and Dean (7) suggested the use of sodium hydroxide as an extractant for the adsorbed phosphate of clay minerals. A clear separation can not be achieved with this reagent, however, because it also dissolves the iron and aluminum phosphates and disperses much of the phosphorus-containing organic matter. The adsorbed form of phosphate has been considered to arise as the result of anion exchange. Stout (25) has postulated a mechanism for the reaction with kaolinite, and Scarseth (23) has reported on the reaction between soluble phosphate and bentonite. The idea of anion exchange by natural and synthetic silicates and hydrogels is not new. Reference to the work of Mattson (15, 16), Gordon (14, 27), Pugh (19, 20), and others is fully given by Murphy (17).

A study of the chemical changes occurring among the various inorganic phosphates in soils depends on the quantitative separation and estimation of each form of phosphate present at various times. A complete characterization of the inorganic soil phosphates would involve a fractionation of the different forms, a description of each, and its quantitative determination. Since the starting point of any fractionation is the determination of some one form, it was decided to study first the equilibrium between water-soluble phosphate and adsorbed phosphate. The work of Kurtz[3] had indicated that successive extractions of a soil with water eventually would remove all of the adsorbed phosphate. Other workers had shown that 0.1 N NaOH would remove the adsorbed phosphate, but since a clear separation of forms can not be attained by this reagent, a more selective extractant was desired. A neutral solution which contains a highly reactive anion would not be open to these objections, and it was thought that such a reagent might extract the adsorbed phosphate from a soil without bringing any other forms into solution.

Such an anion must be extremely reactive, be stable in a neutral solution, offer no complications in the subsequent colorimetric determination of phosphate, and be easily available for purchase. The fluoride ion was the most obvious choice. It is the most highly electronegative of all the anions (11). It is small compared to the other halides or to the phosphate ion (18, p. 189), and its aluminum salt is insoluble. For these reasons it might be expected to replace the lattice OH groups on the surface of kaolinite. Hurst has mentioned the rise in pH when a fluoride solution was added to ceramic clays.[4]

[3] Kurtz, L. T. 1940 Phosphate fixation in Illinois soils. Master's thesis, University of Illinois.

[4] Hurst, T. L. 1940 Doctorate thesis, University of Illinois.

This point can easily be confirmed by adding a few drops of phenolphthalein to a few grams of neutral kaolinite or halloysite and adding 5 to 10 ml. of neutral sodium fluoride. The solution turns pink immediately, indicating a rapid adsorption of fluoride and liberation of sufficient OH ions to raise the pH.

EXPERIMENTAL

Materials used

Kaolinite. The kaolinite used in this work was a china clay from Mitchell County, North Carolina, which had previously been studied by Grim and Bray (12). The whole clay was saturated with NH_4^+ by leaching with a solution of neutral normal ammonium acetate, washing out excess salt with neutral methyl alcohol, and drying at room temperature.

Fractionated kaolinite. The material termed "fractionated kaolinite" had previously been fractionated according to the method of Bray, Grim, and Kerr (1), and contained particles of approximately 0.05 to 1.0 μ effective settling diameter. This material was also saturated with NH_4^+ as described above.

Soil S11215 from the Toledo experiment field, plot 305C, had received no limestone or fertilizers, and no sweet clover had been grown on it.

Soil S11214 from the Toledo experiment field, plot 308B, had been limed and had received 4 tons of rock phosphate, and a rotation of corn, oats, hay, wheat (sweet clover green manure) was followed.

Soil S6757 from the Hartsburg experiment field, plot 410, had received no limestone or fertilizers.

Analytical methods of determining phosphate

Preparation of reagents. The reagents used in determining phosphate were prepared as follows:

Ammonium fluoride for extraction.—Dissolve 37 gm. ammonium fluoride in 200 ml. distilled water. Filter into a 1-liter volumetric flask, dilute to nearly 1000 ml., adjust to a pH of 7.0 with ammonium hydroxide, and make to volume. This is a 1 N NH_4F solution.[5] If more dilute solutions of this stock solution are prepared, adjust each one as above to pH 7.0.

Distilled water for extraction.—All water extractions reported in this paper were made with boiled distilled water.

Ammonium molybdate-hydrochloric acid solution.—Dissolve 15 gm. of C.P. ammonium molybdate in about 300 ml. of warm distilled water (50°C.). Filter if necessary to remove sediment. When the solution has cooled add 350 ml. of 10 N HCl slowly with shaking. Cool this solution to room temperature and dilute to 1000 ml. with distilled water. Mix well and store in a black glass-stoppered bottle. This is a 3.5 N HCl solution containing 0.15

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[5] Since 1 N fluoride solutions slowly attack glass, it is preferable to store the stock solution in a wax-lined bottle.

gm. of ammonium molybdate per 10 ml. This reagent should be replaced by a fresh solution every 2 months.

Stannous chloride, stock solution.—Dissolve 10 gm. of stannous chloride dihydrate in 25 ml. of concentrated hydrochloric acid. This stock solution should be prepared fresh every 2 months. It is preferable to keep this solution in a black glass-stoppered bottle.

Stannous chloride, dilute solution.—Add 1.0 ml. of stannous chloride stock solution to 332 ml. of distilled water. Shake well before use. This solution is the stannous chloride reagent. It deteriorates rapidly and should be made fresh every 8 hours.

Perchloric acid.—C.P., 72 per cent, perchloric acid.

Quinaldine red indicator solution.—Dissolve 0.3 gm. Eastman quinaldine red in 100 ml. distilled water.

TABLE 1

Recovery of phosphate added to 5 ml. normal ammonium fluoride solution after removal of fluoride

P ADDED	P FOUND	RECOVERY
mgm.	*mgm.*	*per cent*
0.0150	0.0183	100.0
0.0000	0.0033*	
0.0150	0.0187	100.6
0.0000	0.0036*	
0.0150	0.0186	97.3
0.0000	0.0040*	

* P found in NH$_4$F blank.

Standard phosphate solution.—All standard phosphate solutions were prepared from dried, C.P. KH$_2$PO$_4$, preserved with 1 per cent formalin and brought to pH 7.0 with NH$_4$OH.

Removal of fluoride.[6] Since the presence of even small amounts of fluoride ion decreases the color in the colorimetric phosphate method, quantitative removal of the ion from the solution is essential. This is accomplished by evaporating an aliquot of the solution in a beaker on the steam bath with 0.5 to 1.0 ml. of concentrated perchloric acid. When the solution has evaporated, the sides of the beaker are washed down with 0.1 N HCl and evaporated again. Table 1 illustrates the recovery by this technic of known amounts of phosphorus added to a fluoride solution. One milliliter of concentrated perchloric acid suffices to decompose a 5-ml. aliquot of N NH$_4$F. A smaller aliquot of fluoride, or a more dilute solution, requires proportionately less perchloric acid.

[6] Solid ammonium fluoride (NH$_4$F) low in phosphate content can be obtained from the Harshaw Chemical Company, Cleveland, Ohio. It is essential to determine the phosphorus in each lot and make the necessary subtraction from the phosphorus in the unknown extract.

Development of color. The perchlorate residue is quantitatively transferred with 0.1 N HCl to a 25- by 200-mm. Pyrex test tube graduated at 35 ml. Five drops of quinaldine red indicator solution are added to the test tube, and ammonium hydroxide is added, drop by drop, until the solution turns a faint pink. To avoid the formation of any precipitate in the neutralization, NH$_4$OH (1+1) is added until the end-point is almost reached. More dilute NH$_4$OH (1+9) is then added until the color changes. The solution is diluted to exactly 35 ml. and the color developed according to the method of Dickman and Bray (8). Ten milliliters of molybdate-HCl reagent is added, the tube inverted three times, 5 ml. of dilute stannous chloride immediately added, and the tube inverted again. The depth of color is determined by placing some of the solution in a photoelectric colorimeter or by visual comparison with an appropriate standard phosphate solution developed similarly to the unknown.

Kaolinitic anion exchange

To place anion exchange on as firm an experimental basis as cation exchange, it is necessary to show that for each milliequivalent of anion adsorbed, 1 milliequivalent of anion is displaced from the silicate colloid. Ten grams of NH$_4$+-saturated kaolinite was shaken intermittently for 4 weeks with 250 ml. of 0.1 N neutral ammonium fluoride. Bromthymol blue indicator was added at the start of the experiment, and as the reaction proceeded, 0.5 N HCl was added to maintain the suspension at pH 7.0 (as judged by the color of the supernatant solution). The milliequivalents of hydroxyls released were calculated from the total volume of acid added and were found to equal 40 per 100 gm. of clay. At the conclusion of the experiment the suspension was filtered, and fluoride was determined in an aliquot of the clear filtrate by weighing as PbFCl (24, p. 405). Forty-one milliequivalents of fluoride were adsorbed by 100 gm. of kaolinite. This value agrees closely with the milliequivalents of hydroxyls released.

Effect of ammonium fluoride concentration on phosphate recovery from kaolinite

Preliminary experiments indicated that solutions of neutral 1 N NH$_4$F when shaken with either soils or kaolinite-phosphate extracted appreciable amounts of phosphate. These results also showed that the time of shaking, the soil-solution ratio, and the fluoride concentration influenced the amount of phosphate extracted. To decrease the possibility of extracting other forms of phosphate, the minimum fluoride concentration, in conjunction with the minimum shaking-time that showed complete recovery of the phosphate added to the kaolinite, was adopted. Various amounts of phosphorus in a 5-ml. volume of neutral phosphate solution were added to 1-gm. samples of NH$_4$+-saturated kaolinite, and the tubes were agitated for a moment to insure adequate contact between the colloid and the phosphate. Fifty milliliters of fluoride solution or of water was added, the tubes were shaken for 1 minute,

and the contents were immediately filtered. The filtrates were centrifuged if they appeared cloudy. The data in table 2 indicate that recovery of virtually all the added phosphate is obtained by 0.1 N NH$_4$F.

Effect of drying on phosphate recovery

Since any adsorbed phosphate that occurs naturally in soils may have been present for comparatively long periods of time and furthermore since soils are usually taken for analysis in the air-dried condition, it was thought desirable to study the effect of drying on phosphate retention. One-gram samples

TABLE 2

Recovery of adsorbed phosphate from kaolinite by water, ammonium fluoride, and sodium hydroxide, with and without drying

EXTRACTANT	P ADDED	P RECOVERED		RECOVERY
		Immediate extraction	Dried overnight	
	mgm.	*mgm.*	*mgm.*	*per cent*
H$_2$O	0.250	0.165		66.0
	0.500	0.363		72.6
	1.000	0.825		82.5
	1.000		0.660	66.0
0.1 N NH$_4$F*	0.250	0.246		98.4
	0.500	0.493		98.6
	1.000	0.995		99.5
	1.000		0.930	93.0
0.25 N NH$_4$F*	0.250	0.253		101.2
0.5 N NH$_4$F*	0.250	0.258		103.2
	1.000		0.940	94.0
1.0 N NH$_4$F*	0.250	0.254		101.6
	1.000		0.940	94.0
0.1 N NaOH	1.000		0.930	93.0

* Corrected for P in blank.

of NH$_4$+-saturated kaolinite were placed in test tubes and 1 mgm. of phosphorus in a volume of 1 ml. was added to each. The mixture was agitated and then dried by drawing air through the tubes overnight at room temperature. Fifty milliliters of extractant was added, the tube shaken 1 minute, the suspension immediately filtered, and the phosphorus determined in an aliquot of the clear filtrate. Table 2 shows the recovery of the added phosphate by water, three concentrations of neutral ammonium fluoride, and 0.1 N NaOH. It is evident that drying decreased recovery, affecting the water extractant to a greater extent than the fluoride or the basic solution.

Influence of particle size of kaolinite on phosphate adsorption

The concentration of phosphate found in any single water extraction of kaolinite-phosphate is the net result of an equilibrium-type reaction. The larger the adsorptive capacity of the material, the less phosphate will be found in solution for any given set of conditions. Murphy (17) has shown that grinding kaolinite in a ball-mill for 6 days greatly increases its adsorptive capacity for phosphate. It is doubtful if the crystal structure of the clay has remained intact after such treatment, and the increase in adsorptive capacity may be due to the creation of types of surfaces which did not exist in the original material.

It was thought that the adsorptive capacity of kaolinite could best be studied by a comparison of the recovery by water of phosphate added to the

TABLE 3

Influence of particle size on recovery of added phosphate from kaolinite

MATERIAL	EXTRACTANT	P ADDED	P RECOVERED BY NH$_4$F*	P RECOVERED BY H$_2$O	P RECOVERY
		mgm.	*mgm.*	*mgm.*	*per cent*
Natural kaolinite..............	H$_2$O	0.250		0.165	66.0
Fine fraction†.................	H$_2$O	0.250		0.121	48.4
Kaolinite.....................	H$_2$O	0.500		0.363	72.6
Fine fraction†.................	H$_2$O	0.500		0.363	72.6
Kaolinite.....................	0.1 *N* NH$_4$F	0.250	0.246		98.4
Fine fraction†.................	0.1 *N* NH$_4$F	0.250	0.250		100.0
Kaolinite.....................	0.1 *N* NH$_4$F	0.500	0.493		98.6
Fine fraction†.................	0.1 *N* NH$_4$F	0.500	0.503		100.6

* Corrected for P in blank.

† 0.05 to 1 μ effective settling diameter.

whole clay with the recovery from the "fractionated kaolinite," which contained a larger proportion of the finer particles than the whole clay. Various amounts of phosphorus in a 5-ml. volume of neutral phosphate solution were added, the tube was shaken for 1 minute, and the solution was filtered and analyzed. Table 3 demonstrates that the water equilibrium with the lesser amount of phosphate has been changed in the fractionated sample; that is, the adsorption per unit weight of kaolinite differs with different particle sizes of the unground material.

The complete recovery of all added phosphate by a 0.1 *N* NH$_4$F extract is evidence that the fluoride ions have destroyed this equilibrium and forced all the phosphate off the clay and into the solution, regardless of the adsorptive capacity of the clay for phosphates.

Influence of time of phosphate-kaolinite contact on phosphate recovery

Murphy (17), Davis (5), Fraps (10) and Hibbard (13) have shown that phosphorus "fixation" is not an instantaneous reaction but that it increases with time. Five-tenths milligram of phosphorus in a 5-ml. volume of neutral solution was added to each of several 1-gm. samples of NH_4^+-saturated kaolinite in test tubes. The tubes were agitated once a day to ensure good contact between the clay and the solution. At the times indicated in table 4, 50 ml. of extractant was added, the solution shaken for 1 minute and immediately filtered. Phosphorus was determined in an aliquot of the clear filtrate. There was an appreciable decrease in the phosphorus recovered with water over a 7-day period. Recovery with 0.1 N neutral fluoride was more constant but also tended to decrease. These data imply that the immediate adsorption is a surface reaction—a polar adsorption—but that many "secondary" reactions may occur during a given interval. Much less is known about the nature

TABLE 4

Influence of period of contact of kaolinite and phosphate on phosphate adsorption by kaolinite

PERIOD OF CONTACT	EXTRACTANT	P RECOVERED*	P RECOVERY
		mgm.	*per cent*
5 minutes....................	H_2O	0.363	72.6
	0.1 N NH_4F	0.493	98.6
3 days.......................	H_2O	0.313	62.6
	0.1 N NH_4F	0.476	95.2
7 days.......................	H_2O	0.291	58.2
	0.1 N NH_4F	0.467	93.4

* After correction for P in blank.

of these reactions than of the adsorption. Further research is necessary to determine whether the "secondary" reactions include the penetration of the phosphorus into the interior of the silicate or whether other adsorption reactions proceed at a slower rate.

Effect of replaceable calcium on phosphate recovery

Both Ravikovitch (21) and Scarseth (22) found that the presence of replaceable calcium increased phosphate "fixation." The kaolinite samples used previously in this work were purposely saturated with NH_4^+ to avoid this complication. Since replaceable calcium is present in most soils in various amounts, however, its effect on the recovery of added phosphate was determined. Kaolinite was saturated with calcium by leaching with 10 per cent calcium chloride, washing out excess salt with neutral methyl alcohol, and drying the residue. Five milliliters of neutral phosphate solution containing 0.25 mgm. of phosphorus was added to a 1-gm. sample of this kaolinite

in a test tube, the mixture was agitated, 50 ml. of extractant was added, the tube was shaken for 1 minute, and the contents were immediately filtered. Phosphorus was determined is an aliquot of the clear filtrate. As shown in table 5 phosphate recovery was decreased with all extractants. The greater recovery obtained with 0.5 N fluoride compared to 0.1 N fluoride indicates that with still greater concentrations of NH$_4$F complete recovery may be possible. Work is now in progress investigating the efficacy of a leaching procedure using 0.1 N NH$_4$F in the determination of the adsorbed phosphate.

TABLE 5

Effect of replaceable calcium and ammonium on phosphate retention by kaolinite

EXTRACTANT	P ADDED	P RECOVERED*		RECOVERY
		Ca^{++} sat.	NH$_4^+$ sat.	
	mgm.	*mgm.*	*mgm.*	*per cent*
H$_2$O	0.250	0.150		60.0
	0.250		0.165	66.0
0.1 N NH$_4$F	0.250	0.225		90.0
	0.250		0.246	98.4
0.5 N NH$_4$F	0.250	0.231		92.4
	0.250		0.258	103.2

* Corrected for P in blank.

TABLE 6

Phosphate extracted from three soils with neutral normal ammonium fluoride

SOIL	SOIL TREATMENT	P EXTRACTED
		p.p.m.
S11214 Toledo	RLrP*	30
S11215 Toledo	0	40
S6757 Hartsburg	0	17

* R = residues, L = limestone, rP = rock phosphate.

Extraction of other forms of phosphate by fluoride

Any quantitative method for a specific chemical form of an ion must necessarily be shown to measure all of the given form that is present. It must also be shown that the results are not influenced by other ions and that other chemical combinations (forms) of the ion being determined are not included. Conclusive evidence that ammonium fluoride measures all the replaceable phosphate and only the replaceable phosphate in soils has not yet been obtained. Indications that this is a likely possibility, however, are presented in table 6. No large difference in phosphorus extracted is found between a check plot and a rock-phosphated soil, when 1 gm. of each is shaken for 1

minute with 50 ml. of neutral normal ammonium fluoride. The Sable silty clay of the Hartsburg soil contains 360 p.p.m. of easily acid-soluble phosphorus but has shown a marked response to superphosphate applications in the last few years. Its fluoride-soluble phosphorus as shown in table 6 is 17 p.p.m. This is one of the smallest amounts found in any soil so far studied. It thus appears that the fluoride reagent may be an aid in determining the chemical forms of phosphate included in the acid-soluble fraction.

SUMMARY

This paper reports a study of anion adsorption by kaolinite. Quantitative evidence demonstrating the stoichiometric replacement of hydroxyl ions by fluoride is presented. The recovery of adsorbed phosphate by shaking with solutions of ammonium fluoride was also studied. It was found that complete recovery of added phosphate was obtained by shaking 1 gm. of kaolinite with 50 ml. of 0.1 N *neutral* NH_4F for 1 minute. Continued phosphate-kaolinite contact, drying, and calcium saturation tended to decrease recovery of added phosphate by this method.

The possibility of measuring the replaceable phosphate of soils and clays with this reagent is discussed. Data are presented which show that this reagent does not extract phosphate resulting from large additions of rock phosphate to a soil, and that it extracts only a part of the phosphate included in the easily acid-soluble fraction.

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EFFECT OF BORAX AND LIME ON ACTIVITY OF SOIL MICROORGANISMS IN NORFOLK FINE SANDY LOAM

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Various factors have been suggested to explain the prevalence of boron unavailability on heavily limed soils. The work of Brioux and Jouis (2) indicated that an insoluble calcium borate is formed. Cook and Millar (3) have suggested that the addition of calcium or magnesium carbonate, and in some cases calcium or magnesium sulfate, to soils renders boron unavailable, whereas sodium as either the carbonate or the sulfate causes no fixation. When soils were treated with sodium, potassium, calcium, and magnesium hydroxides to approximately pH 7.8, Wolf (16) observed boron-deficiency symptoms only on plants growing in the soils treated with calcium and magnesium hydroxides. He also pointed out that "in solution culture tests, a change in pH without a corresponding change in the content of calcium or magnesium in the solution, had little effect on the absorption of boron by plants." On the other hand, Midgley and Dunklee (6, 7) found that calcium, barium, magnesium, and sodium carbonates were equally effective in fixing borates, indicating that fixation was effected by reaction rather than by the material used. They concluded that fixation is chemical rather than biological in nature and is due to activation of certain organic materials by liming.

Midgley (5), Pierre and Browning (11), and others have shown that injury from overliming is usually temporary. It has been suggested by Bobko, et al. (1) and by Naftel (8, 9, 10) that liming of acid soils stimulates microbiological activity to such an extent that the readily available supply of boron in the soil is depleted. The discussion by Jacks and Scherbatoff (4) supports this theory. Investigations by the authors, some of which have been reported (12), indicate that microbiological assimilation and also more rapid plant growth as suggested by Solunskaia (13) may both play a part in the reduction of the available boron supply of limed soils.

EXPERIMENTAL

Preliminary measurements were made of the rate of carbon dioxide evolution from soil treated with various amounts of borax. A slight but consistent

increase in carbon dioxide evolution was found with additions of borax, although microbiological activity was limited by the low organic matter content of the soil. In subsequent tests a readily available source of energy was supplied in the form of dextrose in order to increase microbiological activity.

Norfolk fine sandy loam having a pH of 5.1 and known to be deficient in boron was used in this study. Five treatments in duplicate were included, as follows:

1. No lime, pH 5.1. No borax.
2. No lime, pH 5.1. Borax 10 p.p.m. (20 pounds per acre).
3. Limed, pH 7.7. No borax.
4. Limed, pH 7.7. Borax 10 p.p.m. (20 pounds per acre).
5. Limed, pH 7.7. Borax 20 p.p.m. (40 pounds per acre).

To establish an equilibrium with the limed soil C. P. $Ca(OH)_2$ was added, and the soil was alternately wetted and dried several times. The unlimed soil received the same treatment. In all cases, pH values given are for the soil after the 14-day periods of CO_2 measurement. Nitrogen, P_2O_5, and K_2O from $(NH_4)_2HPO_4$, NH_4NO_3, and KCl were each added at the rate of 100 p.p.m. of air-dry soil. The dry soil, in 200-gm. portions, was placed in 500-ml. Erlenmyer flasks, and borax, dextrose, and fertilizer were added in solution. Moisture was adjusted to 15 per cent, or one-half the water-holding capacity, and the flasks were connected to the respiration apparatus described by Waksman and Starkey (14). Carbon-dioxide-free air was drawn over the soil, and the carbon dioxide evolved was absorbed in 0.1667 N $Ba(OH)_2$ solution. The excess barium hydroxide was titrated daily with 0.1667 N oxalic acid. Three series of measurements were made, each series for 14 days. Dextrose was added to series I at the rate of 250 mgm. per 100 gm. of soil, and to series II and III at the rate of 500 mgm. per 100 gm. of soil. All treatments were inoculated with a suspension of fresh field soil to ensure an adequate population of organisms. The amounts of carbon dioxide liberated from the soil in these three series are shown in table 1.

The rate of carbon dioxide evolution from all treatments reached a peak within 36 to 60 hours after aeration began and then leveled off until at the end of 14 days a small and uniform amount was being evolved. Maximum liberation of carbon dioxide from the acid soil both with and without borax occurred on the second day. Liberation of carbon dioxide from the limed soil both with and without borax reached a peak on the third day. In all cases on both the limed and the unlimed soils, the addition of borax increased the microbiological activity over the corresponding treatments without borax. The average increase in evolution of carbon dioxide for the three series, due to the addition of borax to the unlimed soil, is 7.1 per cent, indicating a deficiency of available boron. A more severe deficiency is shown on the limed soil by an average increase of 15.8 per cent in amount of carbon dioxide liberated, due to the addition of 10 p.p.m. of borax. That this severe deficiency

on the limed soil is due at least in part to increased microbiological activity is evident from the comparison of the amounts of carbon dioxide evolved from the limed and the unlimed soils. The average increase in carbon dioxide evolution due to liming is 8.7 per cent without borax, and 17.4 per cent with 10 p.p.m. borax. The fact that on the limed soil smaller amounts of carbon dioxide are liberated from the 20 p.p.m. borax treatments than from the 10 indicates that the optimum range of boron concentration is rather narrow for microorganisms, as it is for higher plants. Although the application of 20 p.p.m. borax resulted in an average increase in carbon dioxide evolution of 13.4 per cent over the treatment without borax, this was somewhat less than the average increase from the 10 p.p.m. borax treatment.

To determine the numbers of microorganisms at the termination of the aeration studies, soil from each of the three series was plated out. The media used for plating were egg-albumin agar for bacteria and peptone agar for fungi, as described by Waksman (15).

TABLE 1

Effect of borax and lime on carbon dioxide liberation from Norfolk fine sandy loam

Mgm. C per 100 gm. soil in 14 days

Borax.. *p.p.m.* Lime ....?... pH...	0 No lime 5.1	10 No lime 5.1	0 Lime 7.7	10 Lime 7.7	20 Lime 7.7
Series I............................. (250 mgm. dextrose per 100 gm. soil)	154.0	162.7	175.3	181.1	177.3
Series II............................. (500 mgm. dextrose per 100 gm. soil)	235.8	259.2	248.1	301.7	300.3
Series III............................. (500 mgm. dextrose per 100 gm. soil)	256.5	270.5	279.0	330.3	318.6

The total growth of fungi was greatly increased by the addition of borax, especially on the limed soil. Even with the increase due to the applied borax, however, the fungus population of the limed soil never equalled that of the unlimed soil. This is probably due to the elimination of Mucor and Rhizopus on the limed soil, either because of the reaction or the competition of increased numbers of bacteria on this soil. On the unlimed soil, where the growth of Trichoderma is increased by the addition of borax, the population of Mucor and Rhizopus is somewhat decreased, although the total number of organisms is higher on the borax treatment. The growth of both Trichoderma and Penicillium was increased by the addition of borax on the limed soil. The increases in total population of fungi from the 10 p.p.m. borax treatments as compared with the treatments without borax, shown in table 2, agree with corresponding increases in amounts of carbon dioxide evolved, shown in table 1. Decreases in fungus population in series I and III from the 20 p.p.m. borax

treatments as compared with the 10 p.p.m. on the limed soil are also consistent with the amounts of carbon dioxide evolved in these treatments.

A striking difference in types of population due to the different treatments is also shown in table 2. In all series apparently no growth of Mucor and

TABLE 2

Effect of borax and lime on growth of fungi

Numbers per gram of soil

Borax....p.p.m. Lime. pH	0 No lime 5.1	10 No lime 5.1	0 Lime 7.7	10 Lime 7.7	20 Lime 7.7
Series I					
Mucor and Rhizopus spp.	174,500	252,600	......	......	......
Trichoderma spp.	......	......	......	......	......
Other fungi, predominantly Penicillium spp.	......	......	11,600	139,400	18,000
Total	174,500	252,600	11,600	139,400	18,000
Series II					
Mucor and Rhizopus spp.	124,500	99,800	......	......	......
Trichoderma spp.	......	53,800	......	12,400	16,000
Other fungi, predominantly Penicillium spp.	......	......	28,700	71,300	107,000
Total	124,500	153,600	28,700	83,700	123,000
Series III					
Mucor and Rhizopus spp.	126,400	118,500	......	......	......
Trichoderma spp.	4,800	73,800	......	11,100	......
Other fungi, predominantly Penicillium spp.	......	......	17,500	72,000	55,300
Total	131,200	192,300	17,500	83,100	55,300

TABLE 3

Effect of borax and lime on growth of bacteria

Thousands per gram of soil

Borax....p.p.m. Lime. pH	0 No lime 5.1	10 No lime 5.1	0 Lime 7.7	10 Lime 7.7	20 Lime 7.7
Series I	36,561	38,173	40,048	46,359	41,930
Series II	39,155	42,119	46,426	48,854	53,551

Rhizopus was made on the limed soils, and no growth of Penicillium on the unlimed soils. The absence of Trichoderma in series I is possibly due to the depletion of the limited energy supply by the more rapid development of other fungi before the more slowly growing Trichoderma could be established.

In series II and III where Trichoderma species were present, growth of these organisms was confined almost entirely to the borax-treated soils. The possibility of a soil test is suggested here to indicate where response to applications of borax might be expected with higher plants. The effects of both borax and lime on the growth of fungi are shown in plate 1.

The counts of bacteria shown in table 3 are consistent with the counts of fungi and also with the amounts of carbon dioxide evolved from corresponding treatments, although the effect of borax was much less than with fungi. The application of borax increased the numbers of bacteria on both the limed and the unlimed soils.

SUMMARY

The influence of lime and borax on the microbiological activity of Norfolk fine sandy loam is reported. Measurements of amounts of carbon dioxide evolved show that borax increased microbiological activity at both pH 5.1 and pH 7.7. The influence of borax was greater at the higher reaction.

Plate counts show that the fungus population was affected more by the addition of borax than was the population of bacteria. Growth of Trichoderma was confined almost entirely to the borax-treated soil. The possible use of Trichoderma species for a soil test of boron deficiency is suggested.

The data presented indicate that the "fixation" of boron in limed soils is due, at least in part, to the increased activity of the soil microorganisms.

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PLATE 1

EFFECT OF BORAX AND LIME ON GROWTH OF FUNGI

Dilution 1:1000

1. No lime, no borax.   Predominantly Mucor and Rhizopus, very few Trichoderma.

2. No lime, 10 p.p.m. borax.   Predominantly Mucor and Rhizopus, a considerable number of Trichoderma.

3. Lime, no borax.   Predominantly Penicillium, no Trichoderma.

4. Lime, 10 p.p.m. borax. Predominantly Penicillium, a considerable number of Trichoderma.
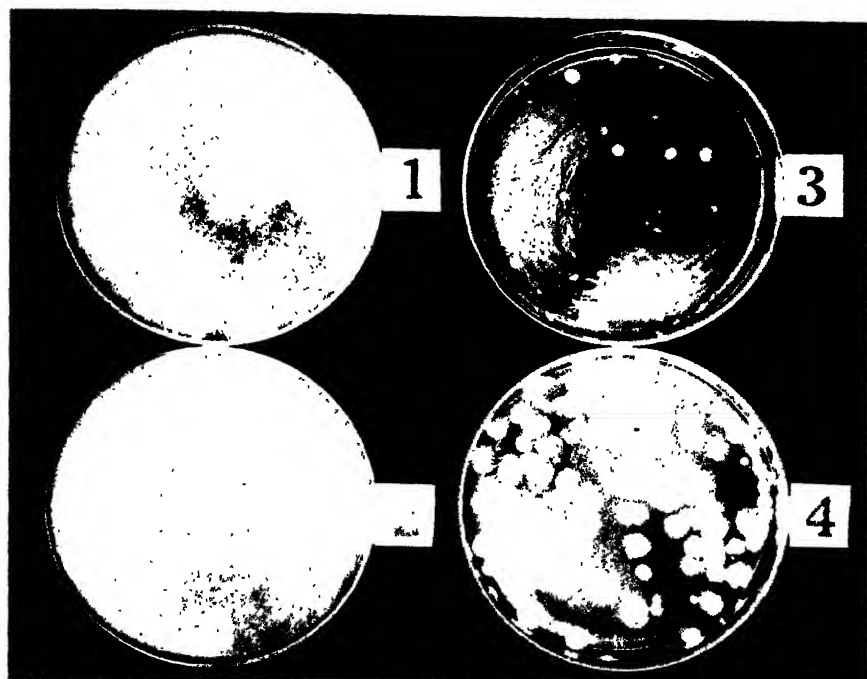
AN IMPORTANT EFFECT OF SOIL COLLOIDS ON PLANT GROWTH

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In a preceding paper (4) we have shown the importance of the space factor for crop yield and its bearing on fertilizing, growing, and breeding plants. The most plausible explanation of the space factor is that living roots excrete toxins, the existence of which was demonstrated by Pickering (5) and has since been confirmed by Pouget and Chouchak (7), Molliard (3), Lumière (2) and others. By excreting toxins, living roots contaminate the soil in their immediate vicinity, and for this reason they are obliged to extend continuously, even though they might find in a small space the nutrients and water necessary for luxuriant plant growth. For the same reason, the space occupied by one plant is unavailable to others and each plant injures its neighbors.

Living-root toxins, according to Pickering (6) are readily oxidized; a 12-hour exposure to the air of water containing them is sufficient to destroy them. In consequence, the addition of substances which, like charcoal, have absorbing and catalytic influences may increase crop yield; in fact, the addition of activated charcoal either to water cultures (8) or to the soil (1) does increase the yield. In passing through charcoal, the water containing the toxins is purified, according to Periturin.[2] It is logical to think that soil colloids may play the same part. If this is so, it would explain the impossibility of obtaining in coarse soils the high yields obtained in fine soils, regardless of the quantities of nutrients and of water added.

In order to elucidate this problem we carried out a series of experiments in the Plant Breeding Institute at Thessaloniki. The purpose of the first experiment was to demonstrate once more the existence of the aforementioned toxins[3] and to show that the coincidental reduction in yield is not due to nutrient exhaustion. The second experiment was designed to show that when many plants are grown in the same solution the yield of each one decreases proportionally and that this fact is not due to solution impoverishment. In the third and fourth experiments the purpose was to show that when the fine-material content of soil is increased the yield increases considerably and this increment is not due to the nutrients contained in these soils or to the increased water-holding capacity.

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[1] Acknowledgments are due my assistant, J. Vantsis, for supervising the experiments.

[2] Reported by Demolon in *Croissance des Végétaux*, Dunod, Paris, 1934.

[3] The existence of living-roots toxins is still denied by certain authors, and the great majority do not attribute to them their real importance.

EXPERIMENTAL

First experiment

On layers of soil 8 cm. thick supported by an iron frame, weeds were grown. Below these layers were placed pots 27 cm. in diameter and 39 cm. deep, filled with 18 liters of a nutrient solution which contained 1 gm. $Ca(NO_3)_2$, 0.333 gm. NaH_2PO_4, and 0.167 gm. K_2SO_4 per liter and which was not in contact with the frame. The roots of the weeds traversed the frame and entered the solution. Pots 9.2 cm. in diameter and 10.5 cm. deep, filled with 870 gm. of a mixture of 2 parts of a sandy soil and 5 parts of gravel and sown with Mentana wheat were watered every day with this solution. After removal of the amount necessary for watering, the solution was brought up to its initial volume by addition of water.

Another group of large pots in which the soil was kept free from vegetation and two other groups filled with a nutrient solution of half the original concentration served as controls. Naturally, the small pots containing wheat were also divided into four groups.

The grain yields of the wheat, in grams per pot, continuously watered with one of the four solutions were as follows:

Strong solution, weed roots....................................	0.588 ± 0.075
Strong solution, no weed roots................................	1.744 ± 0.118
Weak solution, weed roots....................................	0.570 ± 0.075
Weak solution, no weed roots................................	1.368 ± 0.110

The presence of roots in the solution reduced the yield by 67 per cent for the strong solution and by 58 per cent for the weak solution. The difference in yield between the two solution strengths was considerable (20 per cent) when no weeds grew in it, but was insignificant (3 per cent) when weeds grew in it. The influence of the solution strength was many times less than that of the presence of weed roots. If the reduction in yield caused by the presence of the weed roots were due to exhaustion of the solution, the reduction ought to be greater for the weak solution, the difference between the two strengths ought to be greater in the presence of the roots, and the difference between the two strengths ought to be greater than that caused by the presence of the roots.

Second experiment

Wheat plants of the Mentana variety were grown in 2-liter pots filled with a nutrient solution containing 1 gm. $Ca(NO_3)_2$, 0.39 gm. KNO_3, 0.49 gm. $MgHPO_4$, 0.3 gm. $KHSO_4$, and 0.069 gm. $FeSO_4$ per liter. The number of plants per pot was respectively 1, 2, and 3 in three groups. The pots of three other control groups were filled with similar solution but of two-thirds the original concentration.

The grain yields, in grams per plant, were as follows:

Strong solution 1 plant.. 5.25 ± 0.542

                2 plants.. 3.14 ± 0.503

                3 plants.. 1.99 ± 0.117

Weak solution 1 plant.. 4.89 ± 0.290

                2 plants.. 2.67 ± 0.225

The yields per plant were almost exactly inversely proportional to the number of plants, just as in soil. This fact cannot be attributed to the exhaustion of the solutions, for the solutions were strong and the differences in yields between the two strengths were very small in comparison with the differences induced by varying the number of plants per pot.
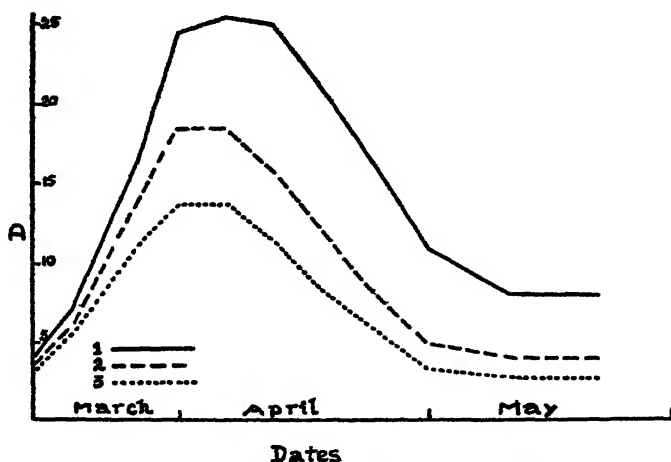
FIG. 1. CURVES OF DENSITY, NUMBER OF TILLERS (D) PER WHEAT PLANT AT DIFFERENT DATES

1, 2, 3 indicate number of plants per pot

Figure 1 shows the density curves (number of tillers at different dates per plant) of this experiment. It is to be noted that the influence of the number of plants per pot increased as growth advanced. This fact is characteristic of the space factor (4).

Third experiment

Pots 22.5 cm. in diameter and 38 cm. in depth were filled with a mixture of fine gravel and fine soil in different proportions and sown with Mentana wheat. This experiment, like the preceding ones, was carried out with two fertilization levels—2.5 gm. $NaNO_3$, 2.5 gm. $Ca(NO_3)_2$, 3 gm. $CaH_4(PO_4)_2$, and 1.5 gm. K_2SO_4 per pot, and one-half of these quantities. The pots were profusely watered many times every day when the temperature rose. All leachates were collected and repoured into the respective pots.

Figure 2 shows the grain yields obtained, in grams per pot, and the density (number of tillers) at heading on April 30. The yields increased considerably
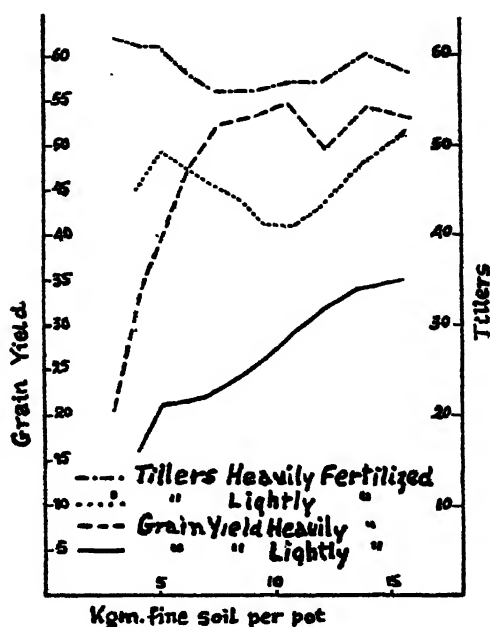

FIG. 2. INFLUENCE OF THE FINE-MATERIAL CONTENT OF THE SOIL ON THE GRAIN YIELD OF WHEAT, IN GRAMS PER POT, AND ON THE NUMBER OF TILLERS AT HEADING

TABLE 1

Influence of the depth of the soil on the number of tillers per pot of Mentana wheat a few days before heading (April 19, 1940) and on the grain yield

POT DEPTH	NUMBER OF TILLERS	GRAIN YIELD	
		Per pot	Per tiller
cm.		*gm.*	*gm.*
Heavy fertilization			
40	28	14.3	0.51
80	29	24.2	0.83
Light fertilization			
40	15	6.6	0.44
80	15	15.3	1.02

when the proportion of fine soil increased. The increments were higher with profuse fertilization. If the influence of the fine materials were due to the nutrients which they contained, addition of such materials ought to be less

TABLE 2

*Corn yields, air-dry weight in grams per pot, of the second order combinations**

Each is the mean of 16 last-order combinations

	$c \times n$			
	n_0	n_1	n_2	n_3
c_1	1.3	4.4	5.1	6.4
c_2	1.9	6.6	10.4	11.8
c_3	2.1	7.5	9.9	13.5
c_4	2.7	8.4	12.2	14.1
	$c \times p$			
	p_0	p_1	p_2	p_3
c_1	0.7	5.3	7.0	4.5
c_2	1.1	8.6	10.8	9.6
c_3	2.–	9.2	9.8	12.1
c_4	2.–	9.2	13.1	13.6
	$c \times w$			
	w_1	w_2	w_3	w_4
c_1	2.5	5.8	4.6	4.1
c_2	4.–	8.7	10.8	7.8
c_3	3.2	9.2	10.6	10.0
c_4	5.–	9.9	11.5	10.9
	$n \times p$			
	p_0	p_1	p_2	p_3
n_0	1.2	2.1	2.2	2.2
n_1	1.5	7.7	9.3	9.0
n_2	1.4	8.9	13.2	14.0
n_3	1.6	13.5	16.1	14.6
	$n \times w$			
	w_1	w_2	w_3	w_4
n_0	1.–	2.1	2.4	2.3
n_1	3.6	7.7	9.7	6.5
n_2	4.7	11.6	11.8	9.4
n_3	5.9	12.2	13.6	14.4
	$p \times w$			
	w_1	w_2	w_3	w_4
p_0	0.9	1.6	1.9	1.4
p_1	3.9	8.8	10.0	9.5
p_2	5.0	11.9	12.6	11.4
p_3	5.5	11.2	13.1	10.5

* w = water, c = clay (fine sand), n = nitrogen, p = phosphorus.

effective when the soil was profusely fertilized.   The density at heading was not affected by the proportion of fine material.   This fact is in agreement with the assumption that fine soil increases the available space, for the importance of the space factor increases as age advances, whereas for nutrients the contrary is true (4).

In an experiment carried out with pots 40 cm. and 80 cm. deep, the density of relatively early growth (at heading) was not influenced by the soil depth, whereas grain yield was doubled (see table 1).   In consequence, the influence of increasing the depth was the same as that of increasing the colloid content of the soil.

Fourth experiment

Pots 12 cm. in diameter and 60 cm. in depth were filled with 7.5 kgm. of a mixture of fine soil and gravel in different proportions (10, 20, 30 and 40 per cent of fine soil).   Each of the four groups was fertilized with four levels of N [0, 400, 800, and 1200 mgm. of 15 per cent $Ca(NO_3)_2$ per pot].   Each of the

TABLE 3

*Corn yield, air-dry weight in grams per pot, of the cardinal combinations**

	n_0p_0	n_0p_3	n_3p_0	n_3p_3
w_1c_1	0.60	1.16	0.50	5.86
w_1c_4	0.48	1.28	0.42	5.76
w_4c_1	0.86	1.62	0.44	3.78
w_4c_4	1.86	4.04	2.72	27.26

Replications, 5; error $\pm$ 0.80.

* w = water, c = clay (fine soil), n = nitrogen, p = phosphorus.

16 groups was fertilized with four levels of P (0, 400, 800, and 1200 mgm. of 16 per cent superphosphate per pot).   Each of the 64 groups was maintained at four levels of moisture (10, 20, 30, and 40 per cent of the water-holding capacity).   The experiment was carried out with single replication of each last-order combination, except the cardinal combinations (see table 3) which had five replications.   The pots were planted to corn on September 2 and harvested October 31.

Table 2 shows the yields of the second-order combinations; table 3, those of the cardinal, or fourth-order, combinations.   By increasing the proportion of fine soil, the yield was always increased (about doubled between 10 and 40 per cent).   The increment in absolute weights was greater with high levels of nitrogen than with low levels, with high levels of phosphorus than with low levels, and with high levels of moisture than with low levels.   The pots fertilized with the higher levels of N and P and maintained at the highest level of moisture gave 27.26 gm. with the highest level of fine soil and only 3.78 with the lowest level of fine soil (table 3).   These increments cannot be attributed to the nutrients contained in the fine soil or to better moisture conditions, for

if this were true the increment ought to decrease when the doses of nutrients or of water increased. The increment is certainly due to another factor, and the most plausible explanation is that clay increased the available space.

SUMMARY

The first of two experiments concerning living root toxins showed that solutions in which roots have grown are deleterious to other plants; the second, that increasing the number of plants grown in a solution reduces the yield proportionally. In both experiments control cultures made under a different level of nutrients showed that these effects are not attributable to an exhaustion of available nutrients.

Two factorial experiments, one with wheat and one with corn, also were carried out in pots with mixtures of fine gravel and fine soil in different proportions and in combination with different levels of nutrients and different levels of soil moisture. The experiments showed that plant yields increase considerably when the proportion of fine materials increases, the increment being greater with high levels of nutrients or moisture than with low levels. Consequently, the increased yield cannot be attributed to the nutrients which the fine materials contain or to their greater water-holding capacity, but must be due to another factor.

The factor concerned is, in the author's opinion, space. The space factor presents the peculiarity that its influence increases as growth advances, whereas for almost all soil factors the contrary is true. In fact, the effect of increasing the proportion of fine soil, though slight at the beginning, became more and more pronounced as growth advanced. In the wheat experiment, the density at heading was much less affected than the grain yield. The effect was the same as that obtained in another experiment by increasing the depth of soil. The explanation is that soil colloids absorb the living root toxins and aid in their oxidation. The effect is analogous to that of charcoal, which is also known to increase the yield of water or soil cultures.

Consequently, in addition to their influence on the chemical and physical properties of the soil, soil colloids have another effect on plant growth; they increase the available space. This effect is considerable. With the highest levels of nitrogen, phosphorus, and water, the yield increased in the corn experiment from 3.78 to 27.26 gm. per pot when the proportion of fine soil increased from 10 to 40 per cent.

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COLLOIDAL ORGANIC ACIDS AS FACTORS IN THE WEATHERING OF ANORTHITE[1]

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The recent demonstration that the inorganic electrodialyzed colloidal clay from the subsoil of Putnam silt loam may be an agency in the weathering of the primary minerals[3] suggests that the colloidal organic acids should produce similar weathering effects. Comparison of the rates of reaction of the various colloidal acids in contrast to those of monomolecularly dispersed acids, like acetic, should show some interesting relationships. The study of these acid behaviors with reference to soil minerals was undertaken in the belief that they and their associated phenomena should lead to a better insight into the problems of soil development and mineral nutrient availability to plants.

The nature of colloidal acids is comparatively well understood by most workers in soil science. In order, however, to avoid confusion, the terminology used in this report is defined as follows: Dissociated hydrogen is the adsorbed hydrogen of a colloidal system which can affect a glass electrode and be responsible for the pH readings. Total hydrogen is all the hydrogen of the system which can be titrated with a standard base, or the milliequivalents of base required to bring the pH of the system to 7.0. Both the dissociated and the undissociated hydrogen comprise the total. It necessarily follows that in an experiment in which one acid is compared with another, it would be rather improbable that both the total hydrogen and the dissociated hydrogen, designated as pH, could be the same, since the degree of dissociation for different colloidal systems is not uniform. It also appears that it would be impossible to keep the total acidity of the system constant without varying the percentage concentration of the colloidal suspension. In this study the total acidity was held constant, and the pH and the concentration were allowed to vary.

PLAN AND METHODS OF STUDY

A pure sample of anorthite was ground finely in a ball mill and placed in a liter cylinder. Distilled water was added, and the fraction ranging in size

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[3] Graham, E. R. Primary minerals of the silt fraction as contributors to the exchangeable base level of acid soils. *Soil Sci.* 49: 277–281, 1940; Calcium transfer from mineral to plant through colloidal clay. *Soil Sci.* 51: 65–71, 1941.

from 0.05 to 0.005 mm. equivalent diameter was separated by means of the beaker method of mechanical analysis. This silt fraction was washed with 0.001 N HCl and then with distilled water to ensure the removal of all ions that might have been released in grinding. The mineral sample was oven dried and reserved for later treatment.

Sodium humate was extracted from peat by adding 4 N NaOH and shaking for several hours. The sodium extract was then electrodialyzed until it was free of adsorbed bases. The pH of the electrodialyzed humus was 3.75. A suspension of this material was prepared and its total acidity measured by titrating against 0.042 N Ca(OH)₂ solution. The end point of this titration (pH of 7.0) was determined by using the glass electrode. The total acidity of the humic acid suspension was found to be 0.49 m.e. per 100 cc.

In a similar manner, a colloidal acid of agar was prepared by electrodialyzing agar until it was free of bases. The suspension of agar thus obtained had a pH of 2.35 and a total acidity of 1.5 m.e. per 100 cc.

For comparison with the two colloidal organic acids, an electrodialyzed sample of bentonite was prepared. This had a pH of 2.3 and a total acidity of 81.5 m.e. per 100 gm. of bentonite.

Each of the three acids was added to prepared anorthite in such quantity that the total hydrogen acting on the anorthite was 3.4 m.e. per 10 gm.

As an illustration of a monomolecular acid, a standard solution of acetic acid was added to anorthite likewise in such quantity that the total acidity was equal to 3.4 m.e. per 10 gm. of anorthite. Such a solution of acetic acid had a pH of 2.8.

The mixtures of anorthite and acid were allowed to stand for 30 days before the first pH determinations of the mixtures were made. These determinations were repeated every 30 days for 3 months, after which analyses were made to determine the amount of calcium transferred from the crystals of the anorthite.

The calcium of the humic-acid-anorthite mixture and that of the agar-anorthite mixture were determined by removing the excess silt anorthite, electrodialyzing the suspension, and analyzing the solution collected in the cathode chamber.

The bentonite-anorthite mixture was treated with normal ammonium acetate and centrifuged until the supernatant liquid was clear. This process was repeated three times to ensure the removal of all the exchangeable calcium. The calcium content of the combined supernatant liquids was determined.

The calcium made soluble by the action of acetic acid on the anorthite was determined by an analysis of the filtrate from the acetic-acid-anorthite mixture.

EXPERIMENTAL RESULTS

The pH of all the mixtures of anorthite and acid increased throughout the reaction interval. In some instances the change was very rapid; in others,

rather slow, as is evident from the data represented in figure 1. It is particularly significant that the pH changes of the mixtures with H-humate and with H-bentonite were the most rapid.

The results of the calcium analysis, presented in table 1, show that significant amounts of calcium were weathered by each acid. The portion of the
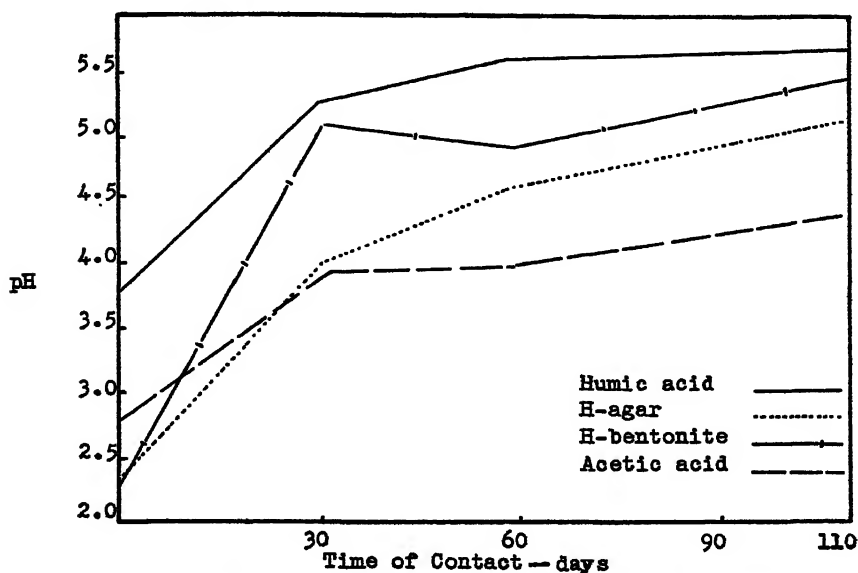

FIG. 1. CHANGES, WITH TIME, IN THE pH OF ACID-MINERAL MIXTURES

TABLE 1

Calcium weathered from anorthite by the action of colloidal and monomolecularly dispersed acetic acids

ACIDS*	CALCIUM
	mgm.
Humic acid..	40.8
H-agar..	37.2
H-bentonite...	48.8
Acetic..	27.6

* The total acidity was 3.4 m.e. acting on 10 gm. of anorthite for 110 days.

total calcium weathered from the anorthite during the 110 days was 3.6 per cent by H-bentonite, 2.9 per cent by humic acid, 2.6 per cent by H-agar, and 2.0 per cent by acetic acid.

DISCUSSION

The results obtained in this study show a definite weathering effect on anorthite by all the acids. The humic acid and the electrodialyzed agar,

both of which are organic acids, were very effective weathering agents. H-bentonite, a colloidal mineral acid, was the most effective agent; and acetic acid, a monomolecular acid, the least.

The initial pH of the humic acid was but 3.75 as compared to 2.35 for the H-agar, yet the amount of calcium weathered by the humic acid was slightly greater than that weathered by the H-agar. The concentration of the hydrogen dissociated from the H-agar system was 25.2 times as great as that from the humic acid system, yet the H-agar system did not weather any more calcium from anorthite than did the humic acid. In fact, the humic acid with less dissociated hydrogen weathered out more calcium. A similar observation was made in a comparison of the action of H-bentonite with H-clay from Putnam subsoil in a previous study. The H-bentonite at an initial pH of 2.3 weathered 48.8 mgm. of calcium from 10 gm. anorthite, whereas the H-clay at an initial pH of 3.3 weathered 48.1 mgm. In this case the dissociated hydrogen of the bentonite system was 10 times as much as that from the Putnam clay. The total acidity in all systems was the same.

From the smaller amount of calcium made soluble by the acetic acid, one might infer that the dissociation of calcium acetate must reduce the rate of solvent action and that the degree of dissociation of calcium from the surface of the colloidal micelle must be rather low. This interesting problem will be further studied by comparing the weathering effect of hydrochloric acid and oxalic acid on the feldspar.

The importance of colloidal clay in weathering primary minerals and in transferring nutritive cations from mineral to plant has been demonstrated.[4] These demonstrations were made with highly selected minerals and at extremely low levels of saturation brought about by laboratory techniques. In interpreting the laboratory results in the light of field conditions, the following aspects might be considered: The nature of the colloidal fraction of the soil is such that it would be rather difficult to isolate the separate effect of the inorganic and the organic colloidal acids. Hence, it is rather important that both systems have behaved similarly. The colloidal clay of the Putnam subsoil has been shown to contain approximately 2 per cent of highly colloidal stable organic matter.[5] In surface soils the percentage organic matter would be much higher and become increasingly important. The organic fraction has always been considered especially important as a dynamic factor in soil fertility. Special importance has been attached to the nutrients held in stock and made available by decomposition processes. Just what the role of the organic fraction has been after it has reached the colloidal phase or the more stable end of its decomposition cycle, however, has not been fully understood. The colloidal organic matter thus formed as a result of decomposition, could be especially effective in transferring nutritive cations from silt and sand grains to the exchange atmosphere of the colloid, thus making these cations available

[4] See footnote 3.
[5] Ferguson, C. E. Unpublished data.

to the plant.   Unsaturated colloidal organic matter in soils has been reported by several workers.   Milne[6] reported tropical soils containing 4 per cent organic matter, which was prinicpally unsaturated.   In considering how unsaturated soil colloids might become, it appears logical that in certain restricted areas near a plant root the saturation of the colloid might reach a very low level.   This would be especially true if the moisture content were below the moisture equivalent so that ion migration would be slowed down.   If we suppose that this happens, saturation could be brought up by one of several agencies; namely, migration of ions from other colloidal particles, cylic decomposition of the organic matter stock, transfer from the crystal lattice of the inorganic soil colloid, or hydrolytic weathering of the silt and sand separates.   In the last case the weathering could be by hydrolysis of carbonated solution, by the action of various free acids, or by the transfer brought about by a colloidal acid.   It also appears highly logical that if soil colloid was found to be largely unsaturated, one could conclude that the percentage of silicate in the silt and sand fraction would be very low and that calcium-bearing feldspar would be almost absent.

SUMMARY AND CONCLUSIONS

A study of the weathering of anorthite by organic colloidal acids and other acids gave the following results:

In 110 days, H-humate, H-agar, H-bentonite, and H-acetate weathered anorthite effectively.

The H-bentonite, H-humate, and H-agar weathered more calcium than the monomolecularly dispersed acetic acid.

The dissociation of the hydrogen from the micelle of the colloidal acid was not a factor, since systems with comparatively small amounts of dissociated hydrogen weathered as much calcium from anorthite as others, when the total acidity was the same.   These results indicate that the colloidal humus of soils, if unsaturated, may become an effective agent in transferring bases from the crystal of primary minerals to the colloidal portion of the soil.

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INTAKE OF CERTAIN ELEMENTS BY CALCIPHILIC AND CALCIPHOBIC PLANTS GROWN ON SOILS DIFFERING IN pH[1]

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Optimum quantity or quality of crops has not been obtained from soils having a comparatively high degree of acidity. The following problem was undertaken, therefore, in an attempt to learn more about the relative action of an acid and a basic soil upon plant growth. The chemical composition of the plant was given especial attention, inasmuch as it is essential from the nutritional standpoint and serves as a comparative measure of the available plant food under the given conditions. The relative behavior of two groups of plants, namely, calciphilic, those producing optimum growth on high-calcium soils, and calciphobic, those capable of producing optimum growth on soils relatively low in calcium, was observed.

EXPERIMENTAL PROCEDURE

The soil

The soil used in this experiment was Chenango loam obtained along Tuscarawas River, Ohio. It was a second terrace soil derived from sandstone and shale. The profile consisted of a brown mellow topsoil, a yellow-brown friable subsurface soil, and a gravelly substratum below 20 to 30 inches. It was medium in fertility, low in pH, and extremely responsive to fertilizers.

Eight pounds of the air-dry soil was put into each of sixty 1-gallon crocks. A base fertilizer consisting of 1.27 gm. of urea, 2.45 gm. of potassium phosphate, and 0.658 gm. of potassium chloride, was added to each crock. The sixty crocks were then divided into two equal groups, A and B. To each crock in group B was added 12.5 gm. of calcium hydroxide, enough to raise the pH of the soil to 7.3±, according to the Veitch lime requirement method. The pH of group A, which received no calcium hydroxide, was 4.4. The soil was kept moist for 2 weeks prior to planting.

The crocks were then packed in sawdust and placed in small cars on a track running in and out of the greenhouse so that the plants to be grown could be kept in the open when the weather permitted.

The plants

Ten plants were selected on the basis of their sensitivity to acid soil. On this basis they may be classified as follows: calciphilic, those needing an abundance of calcium; calciphobic, those needing a comparatively small amount of calcium; and intermediate, those midway between the other two classes in their need for calcium. These plants are listed in table 1.

Seeds were planted in the crocks of groups A and B, three crocks of each plant being grown in each group. After the seed had germinated, the seedlings

TABLE 1

Classification of certain plants on the basis of sensitivity to acid soil

Small grains*		
1. Barley......................	*Hordeum vulgare*	Calciphile
2. Wheat.......................	*Triticum vulgare*	Intermediate
3. Oats........................	*Avena byzantina*	Calciphobe
Legumes		
4. Sweet clover (annual)..........	*Melilotus alba annua*	Calciphile
5. Cowpeas....................	*Vigna sinensis*	Intermediate
6. Peanuts.....................	*Arachis hypogaea*	Calciphobe
Grasses		
7. Kentucky blue................	*Poa pratensis*	Calciphile
8. Timothy....................	*Phleum pratense*	Intermediate
9. Redtop.....................	*Agrostis alba*	Calciphobe
10. Tomato.....................	*Lycopersicon esculentum*	Intermediate

* Although barley, wheat, and oats are of the grass family, they are referred to as small grains, in order to differentiate between them and Kentucky blue, timothy, and redtop.

were thinned, so that in the crocks of like plants there were equal numbers of seedlings.

The plants were harvested, except for the grasses, at a comparable stage of maturity: the small grains, at the early milk stage; sweet clover and peanuts, when past full bloom; cowpeas, after the pod was fully formed but not filled out; and tomatoes, when the first fruit began to develop. The grasses were clipped upon reaching a height of 6 inches. Three clippings were made so that the length of the growing period would be comparable to that of the other plants.

Immediately after harvest, the plant material was weighed and dried in a steam oven until crisp. After the dry weight was determined, the material was ground and put into tightly stoppered bottles for future analysis.

Methods of analysis

The ashing procedure and the nitrogen determination followed the A.O.A.C. methods (1); calcium was determined by the McCrudden method (6); magnesium, by the Redmond and Bright method (7); potassium, by the Emmert method (2); phosphorus, by the Truog and Meyer method (8); and iron by the Holland method.[2]

RESULTS

Plant growth

Both the green and the dry weights of the various plants are given in table 2. There was no evidence of disease, and better than average growth was noted throughout the season. The differences shown by the plants on the acid and basic soils were, briefly, as follows:

Barley. The plants on the basic soil were slightly taller and greater in diameter than those on the acid soil. These differences disappeared during the 2 weeks previous to harvest.

Wheat. The plants on the two soils were equal in height until head formation began, but those on the acid soil produced more lateral growth than those on the basic soil.

Oats. The plant growth was more luxuriant on the basic soil than on the acid soil.

Sweet clover. Plant growth was uniform on the two soils for the first 4 weeks. After this time, the plants on the acid soil grew rather slowly and at blossom time were smaller and much less hardy than the plants on the basic soil, as shown in plate 1, figure 1.

Cowpeas. The plants on the acid soil grew faster, and were larger and more vigorous throughout the growing period. Two weeks previous to harvest, they appeared to stop growing and their characteristic dark color began to fade. As the plants on the basic soil continued to grow normally until harvest, they approached the plants on the acid soil in size and vigor (pl. 1, fig. 2). The foliage remained dark green throughout the growing season.

Peanuts. The plants on both soils grew at the same rate for the first 3 weeks. After this time the plants on the acid soil grew much faster than did the plants on the basic soil (pl. 1, fig. 3). The plants on both soils maintained a dark green color.

Tomato. Growth on the acid soil was not so uniform as that on the basic soil. The plants on the basic soil were uniform and healthy throughout their period of growth. Although the plants on the acid soil started faster, several grew rather poorly, were a lighter green, and tended to send out roots from the stalk.

Timothy-redtop-Kentucky bluegrass. The plants appeared to grow equally well on both soils. The growth on the basic soil was faster after each clipping.

[2] Holland, E. B. Unpublished data. Chem. Dept., Mass. State College, Amherst, Mass.

Ash analysis

Analyses of the ash of the plant material are shown in tables 3 and 4.

Ash content. The percentage of ash was significantly higher in barley, wheat, cowpeas, peanuts, Kentucky bluegrass, timothy, redtop, and tomato on the basic soil than on the acid. Oats and sweet clover had a slightly higher ash content on the acid soil, but the difference was not considered

TABLE 2

*Green and dry weights and percentage of moisture of plants grown on acid and basic soils**

PLANTS		GREEN WEIGHT	DRY WEIGHT	MOISTURE
		gm.	*gm.*	*per cent*
Barley	A	219	39	82.19
	B	346	45	86.99
Wheat	A	189	34	82.01
	B	210	34	83.80
Oats	A	313	43	86.26
	B	358	44	87.70
Sweet clover	A	89	15	83.15
	B	165	34	79.39
Cowpeas	A	599	109	81.80
	B	601	92	84.69
Peanuts	A	281	52	81.49
	B	121	21	82.64
Kentucky bluegrass	A	119	21	82.35
	B	108	18	83.33
Timothy	A	126	16	87.30
	B	121	17	85.95
Redtop	A	147	20	86.39
	B	133	34	74.44
Tomato	A	504	72	85.71
	B	670	102	84.78

* A, acid soil; B, basic soil.

significant. The regularity of increase in ash content was most pronounced among the grasses grown on the more basic soil. The legumes, with the exception of sweet clover, maintained the highest percentage increase of ash when grown on a basic soil, compared with the same plants grown on the more acid soil. The plants classed as intermediates were the most consistent in their increase of total ash on the basic soil. There was no significant difference between the calciphilic and calciphobic plants in this respect.

It is quite evident from these results that the ash content of the various plants was increased by the addition of calcium. This agrees with the results of Gile and Ageton (3), who found that the total carbon-free ash was increased in bush beans, soybeans, radishes, and sunflowers grown on soils that had been treated with calcium carbonate.

There was no correlation in percentage or total insoluble ash of the plants grown on the acid or basic soil. There was an indication, however, that the

TABLE 3

Composition of the total ash in plant material grown on acid and basic soils*
Dry matter basis

PLANTS		TOTAL ASH	INSOLU- BLE ASH	Ca	Mg	N	P	K	Fe
		per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*p.p.m.*
Barley	A	12.06	1.57	0.23	.12	2.88	.48	2.18	168
	B	13.51	0.82	0.82	.17	3.16	.45	2.04	120
Wheat	A	13.18	1.93	0.27	.15	2.83	.44	2.50	282
	B	13.93	2.41	0.50	.18	3.34	.48	1.96	346
Oats	A	12.92	1.52	0.21	.16	2.72	.53	2.66	124
	B	12.85	0.76	0.78	.20	2.86	.45	1.56	146
Sweet clover	A	11.64	0.36	1.27	.41	2.92	.18	2.81	136
	B	11.32	0.27	1.97	.25	2.86	.25	2.49	155
Cowpeas	A	6.64	1.04	0.66	.24	0.93	.22	3.36	130
	B	8.97	0.55	1.88	.38	1.49	.16	3.32	158
Peanuts	A	10.22	0.95	0.77	.40	2.91	.26	2.48	157
	B	13.39	1.32	2.51	.42	3.20	.24	2.74	196
Kentucky bluegrass	A	9.33	1.89	0.36	.20	3.23	.35	2.56	143
	B	1.17	2.02	1.00	.22	3.30	.33	2.64	183
Timothy	A	11.37	1.60	0.25	.13	4.36	.54	2.02	147
	B	14.77	3.29	0.96	.21	4.94	.47	2.44	427
Redtop	A	13.03	1.93	0.28	.27	4.88	.61	1.79	157
	B	14.40	2.90	1.09	.23	4.96	.50	2.43	383
Tomato	A	8.50	1.38	0.43	.15	1.96	.18	3.03	199
	B	12.34	1.18	1.98	.22	2.01	.19	3.27	182

* A, acid soil; B, basic soil.

percentage of insoluble ash was highest in the grasses, and the small grains contained a higher percentage than did the legumes. In total amount of insoluble ash, the small grains were highest, and the grasses were higher than the legumes.

Calcium. The percentage of calcium increased in all plants grown on the basic soil. The legumes were highest in percentage of total calcium on both the acid and the basic soil; the grasses were the next highest; and the small grains were the lowest of the three groups. The intake of calcium by tomato corresponded closely to the intake by the legumes. On the percentage basis there was one and one-half to four and one-half times as much calcium in

plants grown on basic soil as on acid soil. The total amount of calcium was about one and one-half to six times as great in plants grown on basic soil as on acid soil. Iljin (5) reported an increase of twofold to sevenfold among plants grown on calcareous soils compared to those grown on acid soil. In comparing the percentage of calcium and the total calcium in the various plants, it is evident that there is a tendency toward a luxury consumption, especially in the peanut plants.

TABLE 4

*Weight of the total ash constituents in plant material grown on acid and basic soils**
Dry matter basis

PLANTS		TOTAL ASH	INSOLUBLE ASH	Ca	Mg	N	P	K
		gm.	gm.	gm.	gm.	gm.	gm.	gm.
Barley	A	4.7034	0.6123	0.0897	.0468	1.1232	.1872	0.8502
	B	6.0795	0.3690	0.3690	.0765	1.4220	.2025	0.9180
Wheat	A	4.4812	0.6562	0.0918	.0510	0.9622	.1496	0.8500
	B	4.7362	0.8194	0.1700	.0612	1.1356	.1612	0.6664
Oats	A	5.5556	0.6536	0.0903	.0688	1.1696	.2279	1.1438
	B	5.6540	0.3344	0.3432	.0880	1.2584	.1980	0.6864
Sweet clover	A	1.7460	0.0540	0.1905	.0615	0.4380	.0270	0.4215
	B	3.8488	0.0918	0.6698	.0850	0.9724	.0850	0.8466
Cowpeas	A	7.2576	1.1336	0.7194	.2616	1.0137	.2398	3.6624
	B	8.2524	0.5060	1.7296	.2496	1.3708	.1472	3.0544
Peanuts	A	5.3144	0.4940	0.4004	.2080	1.5132	.1352	1.2896
	B	2.8119	0.2772	0.5271	.0882	0.6720	.0504	0.5754
Kentucky bluegrass	A	1.9593	0.3969	0.0756	.0420	0.6783	.0735	0.5376
	B	2.0106	0.3636	0.1800	.0396	0.5940	.0594	0.4752
Timothy	A	1.8192	0.2560	0.0400	.0208	0.6976	.0864	0.3232
	B	2.5109	0.5593	0.1632	.0358	0.8398	.0799	0.4148
Redtop	A	2.6060	0.3860	0.0560	.0540	0.9760	.1220	0.2580
	B	4.8960	0.9860	0.3706	.0782	1.6864	.1700	0.8262
Tomato	A	6.1200	0.9936	0.3096	.1080	1.4112	.1296	2.1816
	B	12.5868	1.2036	2.0196	.2244	2.0502	.1938	3.3354

* A, acid soil; B, basic soil.

In general, these data support those of Hutchings (4) in that calcium added to the soil not only decreases soil acidity, but also aids the plant in producing more tissue, which has a higher percentage content of calcium.

Magnesium. In general, the plants grown on the basic soil contained a higher percentage of magnesium than did the plants grown on the acid soil. Only sweet clover and redtop contained a higher percentage on the acid soil. The three groups of plants show the same general trend in the absorption of magnesium as in the absorption of calcium; namely, the legumes absorbed the highest percentages of magnesium from the soil, and the small grains the low-

est. The tomatoes contained approximately the same percentage of magnesium as did the grasses.

In terms of the total amount of magnesium in the plant tissue, the legumes, in general, contained the highest and the grasses the lowest. The content in tomatoes was analogous to that of the legumes. Peanuts and Kentucky bluegrass contained a higher total amount on the acid soil.

On both the percentage and the total weight basis, the calciphilic, the intermediate, and the calciphobic plants all had a higher content of magnesium on the basic soil. The intermediate plants—wheat, cowpeas, timothy, and tomato—were most outstanding in this respect.

Nitrogen. The total nitrogen on the percentage basis was higher in the plants grown on the basic soil, except for sweet clover. Of the different groups, the grasses contained the highest percentage of total nitrogen. Timothy and redtop were especially high. No significant differences were found in the nitrogen content of the small grains and legumes, except in cowpeas. No explanation can be given at present for the relatively low content of this plant. The tomatoes also had a comparatively low total nitrogen content. Growth of cowpeas and tomatoes did not appear to be abnormal in any way.

In the oven-dry plant tissue, the small grains contained the highest total amount of nitrogen. The grasses contained the lowest total amounts. The content in tomato tissue was comparable to that in the small grains.

The plants classed as intermediates showed the most consistent increase in total nitrogen content on the basic soil.

Phosphorus. The percentage of phosphorus was greater in barley, oats, cowpeas, peanuts, Kentucky bluegrass, timothy, and redtop when grown on the acid soil than when grown on the basic soil. The difference in the percentage of phosphorus in tomatoes on the two soils was not significant. Wheat and sweet clover gave a greater percentage on the basic soil. The phosphorus content of the small grains was of the same relative magnitude as that of the grasses, whereas the content of the legumes was much lower.

The total amount of phosphorus in the different plants was not correlated with the acidity or basicity of the tissue content of the soil.

No correlation of any significance could be found to exist between the calciphilic, intermediate, or calciphobic plants and their phosphorus content.

Potassium. Potassium was the only element determined that did not show any general trend in the plants as a whole. Among the small grains, the percentage of potassium was higher in the plants grown on the acid soil; whereas among the grasses, it was higher in the plants on the basic soil. The legumes were extremely inconsistent in their percentage intake of potassium, that of sweet clover being lower on the basic soil, that of peanuts higher on the basic soil, and that of cowpeas virtually the same on both soils. The intake of potassium by the tomato plants was high on both soils; the greater intake was by the plants on the basic soil.

The total amount of potassium found in the plant is of especial interest. It is evident that several of the plants—oats, cowpeas, and tomatoes—absorbed

a relatively great amount of potassium. These data indicate that the calcium hydroxide added to the soil did not greatly affect the availability of potassium.

There was no significant correlation between the calciphilic, intermediate, and calciphobic plants and their potassium content.

Iron. The intake of iron, in terms of parts per million, was greater in the plants on the basic soil, with the exception of barley and tomatoes, in which the reverse was true. With the exception of wheat, timothy, and redtop, the iron content was uniform throughout. No significant differences were found in the small grains, legumes, or grasses.

In general, the total amount of iron was greater in the tissue of plants grown on the basic soil. Peanuts and barley, on the contrary, showed a greater total intake of iron on the acid soil, but it must be remembered that peanuts produced much more growth on the acid soil than on the basic.

TABLE 5

Change in pH values of Chenango loam as a result of plant growth

PLANT	pH VALUES OF ACID SOIL		pH VALUES OF BASIC SOIL	
	Seeding time	Harvest time	Seeding time	Harvest time
Barley........................	4.4	4.3	7.6	7.2
Wheat........................	4.6	4.5	7.2	7.0
Oats.........................	4.4	4.4	7.3	7.2
Sweet clover..................	4.5	4.1	7.2	6.8
Cowpeas......................	4.3	4.2	7.5	7.1
Peanuts......................	4.4	4.2	7.2	6.7
Kentucky bluegrass............	4.4	4.3	7.4	7.3
Timothy......................	4.5	4.4	7.3	7.2
Redtop.......................	4.5	4.4	7.2	6.9
Tomato.......................	4.4	4.3	7.1	6.9

The calciphilic and the calciphobic plants are relatively inconsistent in their intake of iron. The intermediate plants definitely have a greater intake on the basic soil.

Effect of plant growth on soil pH

As shown in table 5, the pH values of the soil, in general, were slightly lowered as a result of plant growth.

SUMMARY

An investigation was carried out to determine the relative intake of elements by calciphilic, intermediate, and calciphobic plants when grown on acid and on basic soil.

Nine important agronomic crop plants and one vegetable were grown in

crocks of Chenango loam of pH 4.4 and 7.3±. These plants were analyzed for total ash, insoluble ash, calcium, magnesium, nitrogen, phosphorus, potassium, and iron.

The total ash and the intake of calcium, magnesium, nitrogen, and iron increased in the plant when calcium hydroxide was added to the acid soil to raise the pH. In general, the intake of phosphorus decreased with the addition of calcium. Potassium increased or decreased depending largely upon the species of plant grown. The plants grouped as intermediates were consistent in their intake of elements. The calciphobic plants were comparatively consistent, and the calciphiles showed great variability in their absorption of elements.

On the basis of percentage composition, all the plants at higher pH contained more calcium than at lower pH; also under the same condition 80 per cent of all the plants contained more magnesium, 90 per cent contained more nitrogen, and 80 per cent contained more iron. On the contrary, 70 per cent of the plants obtained more phosphorus from the acid soil than from the less acid soil.

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PLATE 1

GROWTH OF LEGUMES ON ACID AND ON BASIC SOIL

The two crocks at the left contain acid soil; the two at the right, basic soil

FIG. 1. Sweet clover.

FIG. 2. Cowpeas.

FIG. 3. Peanuts.

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Fig. 1

Fig. 2

Fig. 3

THE pH OF IRRIGATED ORCHARD SOILS

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Until recently, orchard soils in southern California, with very few exceptions, were considered to be alkaline in reaction. The role that soil moisture plays in the measurement of pH was clarified by the investigations of Salter and Morgan (10). Improvements in the technique of determining the pH of soils have been introduced by McGeorge (9), who, with his associates, has thrown considerable light on the behavior of calcareous soils.

A result of recent studies (4) on the pH relation of trees was the direct determination of the pH of soil *in situ* in the orchard (7). The data presented involved only soils of an experimental orchard at Riverside. The acidity found at low moisture percentages made it desirable to extend the investigation.

METHODS

The methods employed were those recently described (5). Use was made of soil survey maps (2) and other sources of information (1) in determining the soil types. The field moisture percentages are expressed on an oven-dry soil-weight basis. Moisture equivalents (11) were determined in duplicate.

Thirty-gram portions of air-dried (2-mm. screened) soil were used for the pH tests at the 1–5 soil-water ratio.[2]

When the pH values of soil are determined in the field or directly *in situ*, other factors still to be considered are changes in the soil atmosphere and the proximity of sampling or of electrode insertion to active root masses.

Two fundamental differences between soil samples taken with auger or tube and soil samples *in situ* are:

1. Tests of pH on auger or tube samples are made with a stirred sample of soil in which the gaseous equilibrium has undergone some degree of change and in which a uniformity in pH has been induced. *In-situ* samples avoid some of these effects until the samples are removed from the *in-situ* location.

2. The pH values of auger or tube samples represent pH values for a range or interval in soil depth (usually 0.5 or 1.0 foot), whereas the pH values of *in-situ* samples represent pH values for a specific depth or location.

The pH values in the tables were obtained, first, from soil *in situ* and from approximately the same lot of soil after it was stirred and placed in a beaker at

one or more times during the same day, and second, from auger or tube samples treated similarly to *in-situ* samples that had been removed from the soil. The use of improved methods and technique (5, 9) has made it advisable to examine anew, and as widely as possible under orchard as well as under laboratory conditions, the pH of orchard soils.

<div align="center">EXPERIMENTAL DATA</div>

Orchards in Orange County

More than 25 orchard soils were sampled in Orange County, and at the 1–5 s-w.r. in only three instances were the pH values below 7. The data of only eight soils are presented in table 1. The soil survey of the Anaheim area (2) reveals that many of the soils in this county are highly calcareous and may have high water-holding capacity. The pH values at the 1–5 s-w.r. show that many of the orchard soils have potentially high limits of hydrolysis.

The pH values of sandy soils require further study, first, because thin moisture films possibly allow carbon dioxide to escape the more readily and thereby increase the alkalinity, and second, the buffer action of the sandy soils may be so weak that the carbon dioxide production of the roots of well-fertilized or of young trees may result in the pH of soil *in situ* in the proximity of roots being far more acid than stirred soil taken from a root-free area.

The data indicate that among the better orchards, there are soils in which an acid condition exists at one depth or another. The pH values of soils determined in beakers in the field (38 out of a possible 45) were lower than were the values obtained later in the day when the same pH methods were employed with the samples stored in closed containers. The complete data further show that the pH values obtained for soil *in situ* are lower (26 out of a possible 29 cases) than after approximately the same soil sample is stirred and placed in a beaker.

In many of the most productive orchards in this county the soils contain large concentrations of calcium carbonate (6) and the control of soil moisture determines in large measure the continuance of high quality in these orchards.

Data on the pH of grain land (a Redding soil) may also be of interest. All of the soil samples to a depth of 3 feet and at the field moisture percentages (8.6 to 15.4) were acid, the pH values ranging from 5.48 to 6.34 when tested in the laboratory. At the 1–5 s-w.r. the pH values ranged from 6.87 to 9.27. Samplings made in another grain field show the reaction differences of soils taken from the A and B horizons. The moisture equivalents of the soils were: A horizon 6.6 and B horizon 20.3, and the pH values at the 1–5 s-w.r. were 5.51 and 8.52, respectively.

Orchards in Los Angeles County

. Although 23 orchards were tested in Los Angeles County, the results of only 9 are reported in table 1. The tree condition in no. 10 clearly indicated a deficiency of certain minor elements. Orchards 13 and 14 adjoined on similar

TABLE 1

The pH of soils in citrus and avocado orchards in Orange and Los Angeles Counties

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	TESTS IN ORCHARD	TESTS IN LABORATORY		
			pH of soil at field moisture content (in beaker)	pH of soil at field moisture content (in beaker)	pH (1–5 soil-water ratio)	Moisture percentage	Moisture equivalent

Valencia orange (Orange County)

1	Yolo loam	0.5*	5.95	6.61	8.20	14.1	
		1.0	5.82	6.45	8.10	15.3	
		2.0	6.32	7.00	8.46	17.8	
		3.0	6.96	6.78	8.72	13.1	
		3.5†	7.07	6.89	8.74	13.8	
		1.0‡	5.70	5.95	8.05	15.9	25.5
		2.0	6.20	6.17	8.29	15.2	21.9
		3.0	6.75	6.81	8.74	13.3	22.8
		4.0	7.07	7.20	8.88	14.0	
2	Yolo silt loam	0.5	6.17		7.27	14.6	
		1.0	6.47		7.52	19.0	
		2.0	6.63		7.45	23.1	
		3.0	6.70		7.73	24.1	
		4.0	7.12		8.07	26.3	
3	Montezuma clay adobe	0.5	6.80		8.04	37.8 ⎫	48.5
		1.0			8.21	36.5 ⎭	
		2.0			8.24	35.7	47.4
		3.0	6.62		8.40	34.3	51.2
4	Hanford loam	0.5	7.28		8.07	20.5 ⎫	22.1
		1.0	6.87		8.42	20.1 ⎭	
		2.0	6.86		8.36	16.9	20.3
		3.0	6.74		8.06	16.2	21.3
5	Montezuma clay adobe	1.0	5.76		8.24	25.1	48.3
		2.0	6.41		8.13	24.0	48.7
		3.0	6.16		7.34	24.0	39.3
6	Yolo clay loam	1.0	6.76		8.05	18.6	27.1
		2.0	6.49		8.00	17.8	24.0
		3.0	6.06		7.22	15.0	21.3
7	Hanford sand	0.5	6.54		7.68	9.1	6.3
		1.0	7.07		7.88	5.7	4.8
		2.0	7.57		7.84	6.5	5.1
		3.0	7.46		9.01	7.9	5.7

*, † The pH values at these depths were determined *in situ*. Orchard 1: 5.70*, 5.40, 6.12, 6.33, and 6.60† respectively.

‡ In all tables, unless the pH was determined *in situ* it was made on auger or soil tube samples.

TABLE 1—*Continued*

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	TESTS IN ORCHARD pH of soil at field moisture content (in beaker)	TESTS IN LABORATORY pH of soil at field moisture content (in beaker)	pH (1–5 soil-water ratio)	Moisture percentage	Moisture equivalent
Avocado (Orange County)
8	Ramona clay loam	0.5	6.34		7.40	19.1	19.4
		1.0	6.25		7.40	17.8	21.2
		2.0	5.89		6.94	15.6	21.0
		3.0	5.72		7.03	12.8	21.0
		4.0	5.66		6.94	10.4	21.6
Valencia orange (Los Angeles County)
9	Ramona loam	0.5	6.32		6.90	12.5	17.2
		1.0	6.44		7.10	10.6	17.2
		2.0	6.85		7.25	11.1	15.3
		3.0	6.65		7.30	12.5	17.2
		4.0	6.50		7.32	13.1	17.9
10	Hanford coarse sandy loam	0.5	6.91		7.47	10.6	12.2
		1.0	6.95		7.60	8.9	12.2
		2.0	7.33		7.70	8.7	11.5
		3.0	7.48		7.77	8.9	11.8
		4.0	7.21		7.47	10.3	12.6
Washington navel orange (Los Angeles County)
11	Hanford fine sandy loam	0.5	6.42		7.17	13.8 }	13.6
		1.0	6.60		6.90	13.6 }	
		2.0	7.30		7.73	14.7	13.5
		3.0	7.38		7.69	13.0	11.1
12	Hanford fine sandy loam	0.5	6.77		7.00	19.6 }	10.6
		1.0	7.00		7.35	12.3 }	
		2.0	7.40		7.60	10.6	9.3
		3.0	7.26		7.62	10.9	9.2
13	Hanford gravelly sandy loam	0.5	6.42		6.70	12.9 }	13.2
		1.0	6.81		6.87	12.0 }	
		2.0	6.70		6.90	10.4	11.9
		2.5	6.96		7.18	9.8	11.0
14	Hanford gravelly sandy loam	0.5	7.28		7.34	23.2 }	15.9
		1.0	7.30		7.42	14.0 }	
		2.0	6.86		7.80	11.8	13.4
15	Hanford loam	0.5	7.32		7.72	20.7 }	15.5
		1.0	7.22		7.69	14.4 }	
		2.0	7.22		7.40	15.1	16.9
		3.0	6.99		7.22	11.8	16.1
		4.0	6.87		7.11	9.5	

TABLE 1—*Concluded*

| ORCHARD NUMBER | SOIL TYPE | DEPTH IN FEET | TESTS IN ORCHARD | TESTS IN LABORATORY | | |
| | | | pH of soil at field moisture content (in beaker) | pH of soil at field moisture content (in beaker) | pH (1–5 soil-water ratio) | Moisture percentage | Moisture equivalent |

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	pH of soil at field moisture content (in beaker)	pH of soil at field moisture content (in beaker)	pH (1–5 soil-water ratio)	Moisture percentage	Moisture equivalent
Lemon (Los Angeles County)							
16	Hanford or Greenfield sandy loam	0.5	5.77		6.20	15.0	
		1.0	6.06		6.36	14.9	
		2.0	5.91		6.31	12.9	
		3.0	5.51		5.62	9.7	
		4.0	6.26		6.34	9.6	
17	Hanford fine sandy loam	0.5	7.21		7.49	14.5	12.5
		1.0	6.95		7.50	12.8	12.5
		2.0	6.65		7.42	8.4	11.2
		3.0	6.11		7.35	5.2	12.0
		4.0	5.80		7.70	4.7	11.7

soil types. The soils were irrigated with high overhead sprinklers. Manure was applied in both orchards: orchard 14 received manure exclusively while orchard 13 received ammonium sulfate in addition to the manure. The trees in orchard 14 showed minor-element deficiencies whereas those in 13 were healthy.

In orchard 11, acid is used in the irrigation water; in orchard 12 acid is not used. The trees are 40 years old, and the effect of the use of acid in the irrigation water is pronounced without the necessity of changing the pH of the entire soil mass. The 15-year-old double-planted Eureka lemon orchard 16 on sour orange rootstock has an average yearly production of a thousand field boxes per acre. The fertilization program is that of manure and ammonium sulfate.

Orchards in San Bernardino County

Of the 33 orchards examined in San Bernardino County the results for the soils of only 16 are reported in table 2. The 10-acre orchard 18 is an outstanding 47-year-old orchard on sweet rootstock in which no cover crops or weeds, organics, or cultivation has been used since 1912. Calcium nitrate has been applied annually to the soil, and during each of the last 4 years an average production of 400 packed boxes per acre has been obtained. Orchards 19 and 20 are 56 years old. The beneficial effect of the virgin soil was evident. An unused pile of virgin soil showed a pH value of 6.36 at the field moisture content. The soils of orchards 23, 24, 26, and 27 were acid even at the 1–5 s-w.r. (table 2). Orchard 23 was bounded on the upper side by virgin mountain soil, and the old trees for years have been outstanding.

Orchard 28 is an outstanding orchard in an area in which citrus growing is average or below.

TABLE 2

The pH of soils in orange and lemon orchards in San Bernardino County

| ORCHARD NUMBER | SOIL TYPE | DEPTH IN FEET | TESTS IN ORCHARD | TESTS IN LABORATORY | | |
| | | | pH of soil at field moisture content (in beaker) | pH of soil at field moisture content (in beaker) | pH (1–5 soil-water ratio) | Moisture percentage | Moisture equivalent |

Citrus, chiefly Washington navel orange

18	Hanford loam	0.5*	7.13	6.69	8.54	12.2	
		1.0	6.90	6.52	8.68	11.2	
		2.0	7.10	6.62	8.83	10.6	
		3.0	7.05	6.74	8.90	8.0	
		3.5†	7.02	6.76	8.66	10.5	
19	Greenfield sandy loam	1.0	7.12	7.16	7.40	13.0	
		2.0	7.20	7.19	7.35	10.6	
		3.0	7.00	6.95	7.32	11.3	
		4.0	6.96	7.00	7.38	11.7	
		5.0	6.93	7.10	7.42	10.9	
		6.0	7.00	7.20	7.60	10.2	
20	Virgin soil added to part of orchard 19	1.0	6.58	6.91	6.96	12.2	15.3
		2.0	6.50	6.59	6.79	7.3	13.9
		3.0	6.71	6.81	6.95	8.7	15.0
		4.0	6.93	7.10	7.30	9.8	14.8
		5.0	7.10	7.28	7.61	10.1	
		6.0	7.07	7.20	7.58	10.4	
21	Ramona sandy loam	1.0	5.09	5.10	4.86	11.5	
		2.0	5.60	5.58	5.28	12.3	
		3.0	7.40	7.20	7.01	11.2	
		4.0	7.56	7.50	7.05	10.3	
		5.0	7.50	7.28	7.00	7.3	
		6.0	7.21	7.20	7.08	5.4	
22	Placentia loam	1.0	7.23	7.09	7.30	13.0	
		2.0	6.80	6.90	6.92	10.2	
		3.0	6.25	6.23	6.90	14.0	
		4.0	6.30	6.75	7.00	12.4	
		5.0	6.40	6.92	7.03	9.6	
		6.0	6.42	6.70	6.90	8.1	

*, † The pH values at these depths were determined *in situ.* Orchard 18: 6.41*, 7.03, 6.80, 6.80, and 6.49† respectively; additional tests: 6.95, 6.48, 5.85, 6.39, and 6.80; orchard 23: 4.80*, 4.61, 4.54, and 5.42†; orchard 24: 5.30*, 6.03, 6.01, and 6.14†; orchard 25: 6.70*, 6.80, and 6.30†; orchard 26: 6.58* and 6.80†; and orchard 28: 4.71*, 6.10, and 6.18†.

TABLE 2—*Continued*

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	TESTS IN ORCHARD	TESTS IN LABORATORY		
			pH of soil at field moisture content (in beaker)	pH of soil at field moisture content (in beaker)	pH (1-5 soil-water ratio)	Moisture percentage	Moisture equivalent

Citrus, chiefly Washington navel orange—Continued

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	pH of soil at field moisture content (in beaker)	pH of soil at field moisture content (in beaker)	pH (1-5 soil-water ratio)	Moisture percentage	Moisture equivalent
23	Ramona sandy loam	surface*	5.72	5.93	6.03	6.5	
		0.5	4.90	5.29	5.32	8.7	
		1.0	4.71	4.93	5.15	8.1	
		2.0†	5.51	5.80	6.50	4.9	
		0.5	5.70	5.76	5.84	8.7 }	10.8
		1.0	4.62	4.82	4.88	8.8 }	
		2.0	4.92	4.84	5.25	5.8	10.9
		3.0	5.43	5.50	6.30	4.8	11.2
		4.0	5.57	5.73	6.62	4.5	10.8
24	Ramona sandy loam	surface*	6.11	6.30	6.28	9.4	
		0.5	6.02	6.00	6.20	11.6	
		1.0	6.47	6.68	6.65	8.6	
		2.0†	6.58	6.68	6.75	6.4	
		0.5	6.00	6.04	6.29	10.2 }	10.9
		1.0	6.26	6.25	6.32	11.4 }	
		2.0	6.40	6.66	6.69	7.5	8.3
		3.0	6.89	6.80	6.65	6.4	7.0
		4.0	6.79	6.91	6.80	5.7	6.4
25	Placentia sandy loam	0.5*	6.69	7.46	7.30	11.0 }	15.5
		1.0	7.14	7.53	7.18	11.9 }	
		2.0†	7.11	7.47	7.03	13.2	15.8
		3.0	6.40	7.03	6.95	13.2	18.4
		4.0	5.95	6.55	7.10	15.5	
26	Greenfield sandy loam	0.5*	6.60	7.13	7.11	5.7 }	12.3
		1.0†	6.92	7.21	6.98	5.8 }	
		2.0	5.40	5.60	5.55	6.3	12.8
		3.0	6.61	7.29	6.90	8.2	13.6
		4.0	6.87	7.60	7.24	9.6	13.3
27	Greenfield sandy loam	0.5	6.16	6.45	6.30	14.8	
		1.0	5.40	5.61	5.71	11.7	
		2.0	5.14	5.44	5.50	11.3	
		3.0	6.90	7.10	6.78	11.8	
		4.0	7.10	7.35	7.16	12.7	

TABLE 2—*Concluded*

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	TESTS IN ORCHARD	TESTS IN LABORATORY			
			pH of soil at field moisture content (in beaker)	pH of soil at field moisture content (in beaker)	pH (1-5 soil-water ratio)	Moisture percentage	Moisture equivalent
Citrus, chiefly Washington navel orange—Concluded							
28	Hanford fine sandy loam	0.5*	5.65	5.64	5.82	4.9⎫	8.4
		1.0	6.38	6.29	6.30	5.9⎬	
		2.0†	6.57	6.61	6.52	6.8	8.7
		3.0	7.02	6.97	6.74	7.6	9.0
		4.0	7.06	7.11	6.90	8.1	8.9
29	Oakly fine sand over Ramona loam	0.5	6.26		5.59	5.2	
		1.0	5.33		4.91	6.0	
		2.0	6.57		5.87	7.6	
		3.0	7.42		6.72	11.2	
		4.0	7.71		6.86	13.8	
30	Oakly fine sand	0.5	7.56		7.05	6.3⎫	4.0
		1.0	7.82		6.95	5.6⎬	
		2.0	7.48		7.07	6.4	3.4
		3.0	7.90		6.92	7.2	4.0
		4.0	7.31		6.87	9.0	
31	Lugonia sand	0.5	7.20		7.40	8.3	
		1.0	7.13		7.45	7.9	
		2.0	7.40		7.53	8.0	
		3.0	7.43		7.63	8.0	
		4.0	7.42		7.68	8.9	
Lemon							
32	Hanford stony sandy loam	0.5	6.79		7.62	19.1	13.2
		1.0	7.18		7.62	13.7	10.9
		2.0	7.21		7.48	11.4	9.6
33	Hanford stony sandy loam	0.5	5.77		6.48	13.4	11.8
		1.0	5.56		6.20	11.6	9.8

When 2 to 3 feet of sand covered the dense subsoil in orchard 29 overirrigation brought severe injury to the 50-year-old trees while with greater depths of sand in the adjoining orchard 30, growth has been excellent under well-controlled irrigation. With lower percentages of moisture than those given in table 2, the pH values decrease greatly. The temporary drying or aeration in a soil, which lowers the pH and changes the solubilities of nutrient elements, is generally essential for healthy growth in citrus. The pH data for orchard 31 are typical of the soils of a large number of orchards the trees of which show symptoms of minor-element deficiencies.

The soils planted to lemons have good drainage; stones of all sizes and in varying abundance are encountered. In the two excellent orchards, 32 and 33, the soils become more open and of decreasing moisture equivalence as the depth increases. The relation between the time of making the pH determinations and that of the application of the fertilizer, may be evident from a study of orchard 32. This orchard has utilized dairy manure exclusively during the last 8 years and it is applied all at one time near the end of the year. The pH determinations reported were made a few weeks after the manure was applied. Laboratory experiments have shown that manure temporarily at least may increase the pH of some soils. Orchard 33 has used no manure for the last 5 years, depending entirely on complete commercial fertilizers. Neither orchard grows a cover crop. Orchard 33 is the highest ranking orchard in the county. Orchard 32 is excellent, although it was frozen severely in 1937.

In another excellent lemon orchard on Hanford loam with moisture percentages close to the moisture equivalents, which ranged from 16.4 to 19.8, the pH values of the soil were 6.33, 6.67, 6.90, and 6.90 respectively for the 0.5-, 1.0-, 2.0-, and 3.0-foot depths.

Orchards in Riverside County

In Riverside County, opportunity was provided to obtain pH readings of the soil *in situ* in deep trenches. The results obtained in 9 of the 20 orchards sampled are reported in table 3. In a given orchard the first location sampled was between the irrigation furrows, and the second location was under the furrows. The pH values *in situ* under the furrows are not materially different from those obtained between the furrows. One important factor must be taken into consideration in comparisons and in conclusions regarding the pH of soil under the trees, at the drip of the trees, and between the tree rows, and that is, unless the soil moisture percentages are the same in the various locations, the importance of the comparison may be most limited.

Orchards 34 to 38 inclusive are 40 to 50 years of age and are among the highest ranking in the county. Orchard 39 is typical of a large number of orchards deficient in available zinc. Lemon orchard 40 consists of 5 acres of 30-year-old Eureka lemon leafy type trees with an annual production of nearly one thousand field boxes per acre. Orchard 42, consisting of 25-year-old trees (22 trees per acre), produces a ton of nuts per acre. The data for pH *in situ* show that variations occur within relatively short distances in the soil. The closer to the technique of *in situ* that the pH determinations can be made, the more nearly representative are the values obtained for the actual growth conditions.

Orchards in Tulare County

In the 17 orchards studied in Tulare County many of the soils had high moisture equivalents (table 3). Orchard 43 consisted of 20 acres of excellent trees with an average annual production of 10 to 12 field boxes. It was in

TABLE 3

The pH of soils in citrus and walnut orchards in Riverside and Tulare Counties

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	TESTS IN ORCHARD	TESTS IN LABORATORY			
			pH of soil at field moisture content (in beaker)	pH of soil at field moisture content (in beaker)	pH (1-5 soil-water ratio)	Moisture percentage	Moisture equivalent
Washington navel orange (Riverside County)							
34	Hanford sandy loam	0.5*	7.08	6.40	8.05	5.2	
		1.0	7.11	6.89	7.50	7.5	
		2.0	6.20	6.22	7.67	3.5	
		3.0	6.20	6.00	7.76	3.5	
		3.5†	6.22	6.22	7.90	3.6	
		0.5‡	6.35	6.41	8.01	4.4	
		1.0	6.48	6.52	7.42	6.9	
		2.0	5.68	6.06	7.64	4.0	
		3.0	5.74	6.14	7.84	3.4	
		3.5§	6.07	6.00	7.45	3.6	
35	Placentia loam	0.5*	6.71	6.90	7.96	13.1	
		1.0	6.83	6.70	7.86	11.0	
		2.0	7.20	7.30	7.93	13.6	
		3.0	7.17	6.99	8.36	11.9	
		3.5†	7.12	6.21	8.28	11.3	
		0.5‡	7.00	6.59	7.36	11.5	
		1.0	6.90	6.79	7.35	10.9	
		2.0	6.58	6.79	7.83	12.6	
		3.0	6.26	6.59	8.29	11.5	
		3.5§	6.32	6.70	8.34	10.1	
36	Yolo loam, high fan phase	0.5*	5.42	6.14	7.71	17.0	
		1.0	5.44	6.26	7.35	14.7	
		2.0	6.03	6.20	7.40	15.4	
		3.0	6.40	6.45	7.62	13.8	
		3.5†	6.48	5.90	7.73	12.2	
		0.5‡	5.30	6.14	7.88	12.7	
		1.0	5.10	5.82	7.36	13.3	
		2.0	5.61	5.70	7.54	13.5	
		3.0	6.09	6.36	7.57	11.8	
		3.5§	6.62	6.70	7.80	11.0	

*, †, ‡, § The pH values at these depths were determined *in situ*. Orchard 34: 6.07*, 6.15, 5.48, 5.62, and 5.21†; and 5.56‡, 6.00, 5.00, 5.19, and 5.74§ respectively; orchard 35: 5.67*, 6.58, 6.22, 6.20, and 6.10†; 6.48‡, 6.50, 6.71, 5.80, and 6.40§; orchard 36: 5.50*, 5.78, 6.03, 6.18, and 6.29†; 5.14‡, 5.12, 5.80, 5.86, and 6.33§; orchard 37: 5.76*, 5.31, 5.14, 5.68, and 6.39†; 5.70‡, 5.69, 5.45, 5.62, and 6.10§; orchard 38: 4.69*, 5.40, 5.58, 5.92, and 6.09†; 4.50‡, 5.19, 5.92, 5.48, and 5.35§; orchard 40: 6.00*, 5.10, 6.44, 6.16, and 6.42†; and orchard 42: 5.43*, 6.01, 6.80, 6.30, and 6.84†; 6.52‡, 6.10, 6.25, 6.53, and 6.50§.

TABLE 3—*Continued*

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	TESTS IN ORCHARD	TESTS IN LABORATORY		
			pH of soil at field moisture content (in beaker)	pH of soil at field moisture content (in beaker)	pH (1-5 soil-water ratio)	Moisture percentage	Moisture equivalent

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	pH of soil at field moisture content (in beaker)	pH of soil at field moisture content (in beaker)	pH (1-5 soil-water ratio)	Moisture percentage	Moisture equivalent
			Washington navel orange (*Riverside County*)—*Concluded*				
37	Placentia clay loam	0.5*	5.60	6.48	7.18	18.5	
		1.0	5.38	5.80	6.96	11.4	
		2.0	5.40	5.80	7.45	13.6	
		3.0	5.76	6.30	7.88	14.0	
		3.5†	6.32	6.49	8.40	13.8	
		0.5‡	5.91	6.10	7.60	16.1	
		1.0	5.96	5.97	7.30	17.2	
		2.0	5.83	5.83	7.39	13.6	
		3.0	6.10	6.00	7.78	14.1	
		3.5§	6.10	6.40	8.41	13.5	
38	Hanford sandy loam	0.5*	5.07	5.15	5.20	12.1	
		1.0	6.07	6.12	6.50	10.4	
		2.0	6.20	6.32	6.71	10.1	
		3.0	6.20	6.24	6.90	8.8	
		3.5†	6.50	6.36	7.00	11.5	
		0.5‡	4.98	5.33	5.30	11.0	
		1.0	5.28	6.18	6.54	11.4	
		2.0	5.90	6.10	6.89	9.7	
		3.0	6.14	6.30	6.90	10.3	
		3.5§	6.14	6.20	6.90	12.6	
39	Yolo gravelly loam	0.5	6.76		8.01	13.2 ⎫	16.0
		1.0	7.23		8.18	10.6 ⎭	
	,	2.0	6.61		8.04	7.6	15.4
			Lemon (*Riverside County*)				
40	Hanford sandy loam	0.5*	6.78	6.67	7.41	14.3	
		1.0	5.98	6.06	7.42	5.0	
		2.0	6.80	6.75	8.08	7.8	
		3.0	6.80	6.70	7.82	11.8	
		3.5†	6.64	6.73	7.98	11.0	
41	Madera sandy loam	0.5	6.90		7.60	12.3	9.2
		1.5	5.89		7.42	16.1	21.5
		2.0	5.96		7.62	12.9	18.9
		3.0	6.50		8.23	11.8	14.8
		4.0	6.73		8.45	11.1	13.5

TABLE 3—*Continued*

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	TESTS IN ORCHARD	TESTS IN LABORATORY		
			pH of soil at field moisture content (in beaker)	pH of soil at field moisture content (in beaker)	pH (1–5 soil-water ratio)	Moisture percent-age	Moisture equiva-lent

		Walnuts (Riverside County)					
42	Hanford sandy loam	0.5*	5.80	6.18	6.55	8.1	
		1.0	6.73	6.82	7.37	7.1	
		2.0	6.95	6.83	7.53	9.0	
		3.0	6.65	6.81	7.60	6.9	
		3.5†	6.86	6.58	7.73	6.8	
		0.5‡	6.51	6.63	6.70	14.4	
		1.0	6.32	6.50	7.09	8.6	
		2.0	6.40	6.80	7.40	12.6	
		3.0	6.64	6.88	7.60	10.5	
		3.5§	6.78	6.94	7.79	9.8	

		Washington navel orange (Tulare County)					
43	Hanford sandy loam	0.5	5.24		5.51	12.9⎫	9.5
		1.0	5.66		6.14	9.8⎭	
		2.0	5.90		6.73	8.3	6.8
		3.0	6.20		6.98	9.5	7.3
		4.0	6.45		7.04	8.9	13.2
44	Hanford coarse sandy loam	0.5	6.81		7.41	12.1⎫	12.5
		1.0	6.83		7.48	9.0⎭	
		2.0	6.79		7.33	10.6	12.2
		3.0	6.58		7.20	9.7	11.6
		4.0	6.49		7.14	8.8	13.9
45	San Joaquin sandy loam	0.5	5.20		6.02	11.1⎫	12.4
		1.0	5.45		6.02	9.7⎭	
		2.0	5.26		6.10	7.3	10.1
		3.0	5.89		7.20	7.3	14.6
		4.0	6.14		7.49	7.6	14.9
46	Porterville clay loam adobe	0.5	6.31		7.97	31.8⎫	36.6
		1.0	6.24		8.20	29.3⎭	
		1.5	6.42		8.50	26.6	34.0
		2.0	6.32		8.70	26.0	34.0
		2.5	6.50		8.82	25.8	35.1

TABLE 3—*Concluded*

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	TESTS IN ORCHARD — pH of soil at field moisture content (in beaker)	TESTS IN LABORATORY — pH of soil at field moisture content (in beaker)	pH (1-5 soil-water ratio)	Moisture percentage	Moisture equivalent
Washington navel orange (Tulare County)—Concluded						
47	Porterville clay loam adobe	0.5	6.64		8.29	24.6	30.3
		1.0	6.65		8.61	22.3	30.3
		1.5	7.07		8.77	22.6	30.4
		2.0	7.25		8.92	22.9	30.4
		2.5	7.08		8.83	23.1	
		3.0	7.07		8.78	23.2	30.3
48	Porterville clay loam adobe	0.2	5.42				
		0.2	5.82				
		0.5	6.16		8.19	22.2	
		1.0	6.48		8.65	23.2	
		1.5	6.47		9.04	23.4	
		2.0	6.44		9.20	21.9	
		2.5	6.31		9.33	18.7	
49	Porterville clay loam adobe	0.5	6.40		8.30	25.5	40.4
		1.0	6.10		8.34	23.7	
		1.5	6.15		8.45	21.5	39.5
		2.0	6.05		8.41	18.9	
Lemon (Tulare County)						
50	Porterville clay loam	0.5	5.67		8.11	18.2	25.4
		1.0	6.26		8.61	17.8	
		1.5	6.42		8.72	18.1	26.9
		2.0	6.57		8.83	19.1	

orchard 44 that Johnston (8) first conducted some of his zinc trials. These trees had been severely mottled until zinc sprays were used. The trees in orchard 45 were large and in excellent condition. In orchard 46 the soil was very heavy. The data for samples from the higher part of the orchard confirm the fact that the soil is highly calcareous. In some parts of the orchard in which soil moisture can be controlled the leaves are dark green and healthy. In other areas the high soil moisture content permits hydrolysis of the calcium carbonate to such an extent that most of the leaves of certain trees of large trunk diameter (which indicates that the trees were once in a healthy condition) have become chlorotic. This is lime-induced chlorosis. When the soil of such chlorotic areas was tested in the orchard (no. 47), the pH values to a depth of a foot or more showed acidity, but at the lower depths the soil was slightly alkaline. The continuity of the high moisture content of the soil

in a chlorotic tree area maintains a high pH value that reduces availability of essential ions. Orchard 48 is considered as the highest standard for other orchards in its locality. The trees are 15 years old, the leaves are of good color, and the soil contains abundant calcium carbonate. However, the soil in this orchard was acid to a depth that includes much of the root system. The soil in orchard 49 is a clay loam adobe. Care must be exercised in the application of irrigation water. The trees, small for their age, are healthy. Orchard 50 is an outstanding orchard in a highly calcareous soil area. The calcareous soils form some of the most productive citrus areas but require skillful management of soil moisture.

Orchards in Ventura County

The soils of more than 26 Ventura County orchards were tested. The orchards in this county (table 4), like those in Orange County, extend close to the ocean and include calcareous soil areas.

The first five orchards (nos. 51–55 inclusive) in table 4 were parts of one large lemon property. Orchards 52 to 55 were plots of the very best trees, relatively young, uniform in age and origin, and separated by suitable guard rows. The uniform soil was a choice location and every cultural care was provided for. Soil samplings were in comparable locations with respect to the irrigation furrow and the position of the trees. Irrigation was by the furrow method. Orchard 52 received no fertilization. Orchard 53, to which ammonium phosphate was applied, is outstanding. Orchard 54 received calcium nitrate. The soil in orchard 55 was drier than that in the other plots when the pH tests were made. In this manure-treated soil, the pH values of the 1–5 s-w.r., in both the half-foot and fourth-foot samples were above 8.00. The pH values of the soil in the manure-treated (no. 55) and in the calcium nitrate-treated (no. 54) plots were generally higher than those of the soil in the ammonium phosphate-treated (no. 53) plot.

From the data for orchards 52 to 55 inclusive it appears that fertilization can affect the pH of orchard soils and that the best results were had with the more acid-forming types of fertilizers. The pH results of orchard 54 (calcium-nitrate fertilized) are confirmed by orchard 56, which is in a separate fertilizer trial nearby on similar soil.

The soil in orchard 57 has a high moisture equivalent and is close to areas high in alkaline materials. Control of the irrigation water has made it possible to produce an outstanding orchard in this area. It was from leaves taken in this orchard that Haas diagnosed certain leaf symptoms as those of manganese deficiency, the first such diagnosis made for the citrus areas of California. The diagnosis was confirmed later by Southwick and his associates, who were able to correct this deficiency through the use of sprays containing manganese.

A high boron and sulfate concentration and calcium carbonate hydrolysis, as the pH values increase, are factors affecting orchard 58.

Orchard 59 is an excellent one that has received calcium nitrate until re-

TABLE 4
The pH of soils in citrus orchards in Ventura County

| ORCHARD NUMBER | SOIL TYPE | DEPTH IN FEET | TESTS IN ORCHARD | TESTS IN LABORATORY | | |
| | | | pH of soil at field moisture content (in beaker) | pH of soil at field moisture content (in beaker) | pH (1-5 soil-water ratio) | Moisture percentage | Moisture equivalent |

(Note: columns are: Orchard number, Soil type, Depth in feet, pH of soil at field moisture content (in beaker) — orchard test, pH of soil at field moisture content (in beaker) — lab test, pH (1-5 soil-water ratio), Moisture percentage, Moisture equivalent)

Lemon

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	pH of soil at field moisture content (in beaker) [orchard]	pH of soil at field moisture content (in beaker) [lab]	pH (1-5 soil-water ratio)	Moisture percentage	Moisture equivalent
51	Rincon loam	0.5	7.20	6.95	8.08	11.7 ⎫	20.1
		1.0	6.99	7.12	7.98	13.0 ⎭	
		1.5*	6.01	6.55	7.81	18.3	23.4
		2.0†	5.87	6.30	7.70	18.4	26.0
		2.5	6.05	5.86	7.89	15.9	
52	Yolo loam	0.5*	7.14	7.10	7.40	24.3	
		1.0	7.15	6.85	7.33	18.9	
		2.0†	6.55	6.58	7.12	15.5	
		0.5	7.70	7.55	8.16	18.5 ⎫	18.4
		1.0	7.24	7.01	7.62	17.1 ⎭	
		2.0	7.03	6.98	7.60	12.3	19.3
		3.0	6.48	6.61	7.50	13.8	18.8
		4.0	6.04	6.06	7.32	15.5	19.3
53	Yolo loam	0.5*	6.28	6.44	6.18	20.2	
		1.0	6.75	6.69	6.33	20.4	
		2.0†	6.20	6.53	6.30	11.4	
		0.5	6.74	6.75	6.60	19.5 ⎫	19.4
		1.0	7.07	7.22	6.74	19.2 ⎭	
		2.0	6.31	6.30	6.32	12.7	20.9
		3.0	6.05	6.09	6.28	13.9	20.8
		4.0	6.06	6.09	6.28	15.6	20.9
54	Yolo loam	0.5*	7.66	7.50	7.20	20.5	
		1.0	7.24	7.19	6.74	19.9	
		2.0†	6.61	6.80	6.46	15.4	
		0.5	7.55	7.51	7.81	20.6	
		1.0	7.48	7.30	7.50	17.9	
		2.0	7.10	7.00	7.06	16.0	
		3.0	6.93	6.70	6.98	13.2	
		4.0	6.10	6.10	6.90	15.1	

*, † The pH values at these depths were determined *in situ.* Orchard 51: (at these depths in another location) 6.60* and 5.00†; respectively; orchard 52: 7.30*, 7.20, and 6.35†; orchard 53: 6.46*, 6.72, and 5.82†; orchard 54: 7.69*, 7.46, and 6.30†; orchard 55: 6.50*, 6.60, and 5.80†; orchard 61: 7.00*, 6.72, 7.10, and 6.53†; and orchard 62: 7.10*, 6.89, 7.02, and 7.10†.

TABLE 4—*Continued*

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	TESTS IN ORCHARD	TESTS IN LABORATORY		
			pH of soil at field moisture content (in beaker)	pH of soil at field moisture content (in beaker)	pH (1–5 soil-water ratio)	Moisture percentage	Moisture equivalent

Lemon—Concluded

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	pH of soil at field moisture content (in beaker)	pH of soil at field moisture content (in beaker)	pH (1–5 soil-water ratio)	Moisture percentage	Moisture equivalent
55	Yolo loam	0.5*	6.75	6.59	7.42	16.7	
		1.0	6.70	6.44	7.32	12.3	
		2.0†	6.28	5.91	6.70	13.1	
		0.5	7.55	7.16	8.05	18.2	
		1.0	6.80	7.03	7.30	15.9	
		2.0	6.53	6.10	6.90	13.4	
		3.0	6.40	5.90	6.59	14.2	
		4.0	7.06	6.45	8.10	13.7	
56	Yolo sandy loam	0.5	7.17	6.90	7.56	16.9	
		1.0	7.00	6.64	7.35	14.8	
		2.0	6.80	6.60	7.40	10.6	
		3.0	6.90	6.75	7.42	7.1	
		4.0	6.91	6.70	7.50	7.5	
57	Sorrento clay loam	0.5	6.36		7.36	20.9 ⎫	31.4
		1.0	6.50		7.40	21.0 ⎭	
		2.0	6.70		8.13	22.8	28.2
		3.0	7.12		8.37	24.6	27.5
		4.0	7.01		8.51	26.7	32.1
58	Sorrento sandy loam	0.5	7.15		8.09	6.5 ⎫	16.0
		1.0	6.53		7.90	9.4 ⎭	
		2.0	6.70		8.10	15.8	24.5
		3.0	7.59		8.09	17.0	23.1
		4.0	7.50		8.06	18.3	20.7
59	Yolo loam	0.5	6.28		7.57	13.5	
		1.0	6.47		8.30	14.0	
		2.0	7.06		8.59	15.5	
		3.0	7.25		8.40	17.8	
		4.0	7.18		8.43	20.3	
60	Rincon loam	0.5	7.25		7.68	17.1 ⎫	20.7
		1.0	7.32		7.86	16.5 ⎭	
		1.5	6.70		7.70	20.1 ⎫	26.5
		2.0	6.04		7.62	17.5 ⎭	
		2.5	6.26		7.70	14.5	

TABLE 4—*Concluded*

| ORCHARD NUMBER | SOIL TYPE | DEPTH IN FEET | TESTS IN ORCHARD | TESTS IN LABORATORY | | |
			pH of soil at field moisture content (in beaker)	pH of soil at field moisture content (in beaker)	pH (1–5 soil-water ratio)	Moisture percentage	Moisture equivalent
			Orange				
61	Yolo loam, brown phase	surface*	7.33	7.19	7.82	24.5	
		0.5	6.97	7.07	7.62	19.5	
		1.0	7.23	7.22	8.50	26.1	
		2.0†	7.12	7.15	8.41	25.5	
		0.5	7.14	7.21			
		1.0	6.85	7.20			
		2.0	6.99	7.07			
		3.0	6.76	6.90			
		4.0	6.81	7.00			
		1.0	6.40	6.57	8.01	9.6	18.9
		2.0	6.40	6.94	8.45	8.6	18.5
		3.0	6.60	6.99	8.33	10.9	21.4
		4.0	6.80	7.20	8.48	16.9	22.7
62	Yolo fine sandy loam, gray phase	surface*	7.18	7.15	7.96	16.1	
		0.5	6.93	7.20	7.91	15.5	
		1.0	6.93	7.13	8.14	16.1	
		2.0†	7.00	7.66	8.42	17.9	
		0.5	6.86	7.10	8.00	13.0	16.5
		1.0	6.90	7.35	8.14	16.0	
		2.0	7.22	7.28	8.50	16.5	17.3
		3.0	7.42	7.70	8.58	18.1	17.1
		4.0	7.35	7.73	8.71	15.7	13.3
		0.5–1.0	7.01	6.93	7.90	9.8	
		1.5	6.63	6.95	8.21	9.6	
		2.0	6.75	6.80	8.40	9.6	
		3.0	7.25	7.22	8.70	13.7	
		4.0	7.25	7.47	8.79	14.1	

cently, when ammonia was used. It is typical of many such orchards in which zinc spraying is necessary. Lemon trees in many orchards remain profitable for periods as short as 15 years, hence any factors that influence the nutrition of the trees become of importance.

In orchards subject to overirrigation and high pH values in the soil, the dry areas in the tree rows frequently are of considerable value in maintaining a fair tree condition. In many furrow-irrigated orchards there may be relatively

few roots in the irrigated area, the principal root masses being in the drier soil in the tree row.

In orchards 61 and 62 the first series of tests in each case were made *in situ*. The second series of tests were also in the irrigated area between the tree rows and were made upon auger samples. The third series of tests were made in the nonirrigated area in the tree row. The moisture percentages in the soil in the tree rows were less than those in the soil between the tree rows. At the field moisture content the soil in the nonirrigated tree rows was more acid than was the irrigated soil between the tree rows. Many other orchard soils could be used to illustrate this same point. Low pH values in soil, which are related to low moisture and high oxygen supplies, favor good root development.

Orchards in San Diego County

More than 25 orchard soils covering a wide range of soil types were sampled in San Diego County. The soil type changes abruptly in crossing from orchard 63 into the adjoining orchard 64 (table 5). Number 63 is an excellent 55-year-old orchard. There is an increasing clay content below the 1½-foot depth. The trees in orchard 64 are on sour rootstock, and the soil is heavy and highly calcareous. In orchard 65 the lemon trees were large. Orchard 66 is an excellent, double-planted lemon orchard. Large old lemon trees comprise the outstanding orchard 67 that is budded on sour orangeroot stock. Systematic pruning has assisted this orchard in avoiding problems of tree decline and has resulted in the production of high-quality fruit. Noteworthy are the acidity values obtained in the excellent lemon orchard 68. It should prove of interest to determine the calcium content in such a soil.

Many of the citrus soils in this area are relatively shallow. Though the trees may be of good color, their size necessarily may be limited by the restricted soil area available for root growth, as in orchard 69. Tree size is limited in orchards 70 and 71 because of dense strata of heavy soil at relatively shallow depths. The trees appear healthy even though dwarfed. They are 9 to 11 years old and have an average annual production of four to five field boxes. In comparison with orchards 70 and 71 are orchards 72 and 73. The outstanding 11-acre orchard (no. 72) of 14-year-old trees has an average annual yield of eight to nine field boxes. In orchard 73 the trees are 13 years old and in excellent condition, the fruit quality being high. The pH values for orchard 74 at the field moisture content show an increasing acidity with increased depth, which may be accounted for in part by the decreasing moisture percentages. The trees in orchard 74 were 40 years old, large and in excellent condition in the area of sampling. In other parts of the orchard, the pH values were higher, and the mottle-leaf condition of the trees indicated a zinc deficiency. The pH values of the samples from the outstanding 11-year-old avocado orchard 75 are very acid (3). In an avocado orchard on Sierra sandy loam with a moisture equivalent of approximately 12, the pH values ranged from 4.44 to 5.80 respectively; at the 1–5 s-w.r. the pH values ranged from

TABLE 5

The pH of a wide range of soils in citrus and avocado orchards in San Diego County

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	TESTS IN ORCHARD pH of soil at field moisture content (in beaker)	TESTS IN LABORATORY pH (1–5 soil-water ratio)	Moisture percentage	Moisture equivalent
Lemon						
63	Olievenhain gravelly sandy loam	0.5–1.0	6.57	7.83	7.8	8.0
		1.5	6.37	7.18	9.1	9.7
		2.0	5.96	7.18	14.5	14.3
		2.5	5.78	7.12	16.8	19.3
		3.0				22.1
64	Diablo clay adobe	0.5	6.15	8.13	12.3	26.4
		1.0				28.4
		1.5	6.00	8.30	13.6	31.8
		2.0	6.28	8.27	14.4	29.6
		2.5	6.30	8.24	16.2	35.2
		3.0	6.26	8.50	14.5	26.5
65	Hanford coarse sandy loam	0.5	5.36	6.30	10.3	
		1.0	6.18	6.93	9.9	
		2.0	6.50	7.08	9.1	9.8
		3.0	6.50	7.20	9.4	9.4
		4.0	6.65	7.13	12.4	10.5
66	Monserate sandy loam	0.5	6.41	6.50	12.0⎫	9.6
		1.0	5.63	5.80	10.1⎭	
		2.0	5.87	6.46	9.9	10.1
		2.5	6.05	6.97	11.3	10.2
		3.0	5.91	7.13	20.6	14.2
67	Fallbrook sandy loam	0.5	5.95	6.21	12.7	
		1.0	6.43	6.87	12.9	
		2.0	6.84	7.47	12.0	
		3.0	6.95	7.25	12.0	
		4.0	6.92	7.28	13.2	
68	Sierra sandy loam	0.5	4.51	5.37	7.4	16.1
		1.0	5.25	5.20	9.2	16.4
		2.0	5.23	5.60	12.3	17.6
		3.0	5.55	6.80	13.7	17.9
Valencia orange						
69	Altamont clay	0.5	6.40	7.80	29.7⎫	29.2
		1.0	6.20	7.79	27.1⎪	
		1.5	6.05	7.58	27.1⎪	31.9
		2.0	5.80	7.58	26.5⎭	
70	Carlsbad loamy fine sand	0.5	6.40	6.95	9.2	9.0
		1.0	6.69	7.12	8.3	9.2
		1.5	7.20	7.46	10.3	9.1
		2.0	7.25	7.51	12.4	12.6
		2.5	6.70	7.24	11.7	21.5
		3.0	5.53	7.40	14.5	18.4

TABLE 5—*Concluded*

ORCHARD NUMBER	SOIL TYPE	DEPTH IN FEET	TESTS IN ORCHARD pH of soil at field moisture content (in beaker)	TESTS IN LABORATORY pH (1–5 soil-water ratio)	Moisture percent-age	Moisture equiva-lent
				Valencia orange—Concluded		
71	Olievenhain sandy loam	0.5	5.95	6.94	11.4	16.5
		1.0	6.12	6.96	12.0	21.1
		1.5	5.17	7.07	16.0	34.6
		2.0	5.71	7.78	17.9	44.4
		2.5	5.88	7.88	17.9	
		3.0	5.68	7.19	19.6	
72	Sierra sandy loam	0.5	5.52	6.32	6.1 ⎫	10.1
		1.0	5.87	6.43	8.0 ⎭	
		2.0	5.85	6.95	9.1	13.4
		3.0	5.75	7.21	8.3	13.6
		4.0	5.96	7.60	9.0	
73	Greenfield sandy loam	1.0	6.38	6.60	11.1	
		2.0	6.35	6.62	11.5	
		3.0	6.40	6.86	13.3	
				Washington navel orange		
74	Ramona sandy loam	0.5	7.04	7.14	10.4	
		1.0	6.91	7.28	8.5	
		2.0	6.61	7.15	9.0	
		3.0	6.20	7.23	4.8	
		4.0	6.23	7.42	4.5	
				Avocado		
75	Vista sandy loam	0.5	4.65	5.27	10.4 ⎫	9.5
		1.0	4.98	5.42	7.8 ⎭	
		2.0	5.25	5.71	8.6	9.0
		3.0	5.57	6.35	8.6	8.6
		4.0	6.07	6.67	8.9	8.1
76	Sierra sandy loam	0.5	6.21	6.74	14.6 ⎫	12.0
		1.0	6.15	6.99	12.2 ⎭	
		2.0	6.39	7.33	11.2	11.4
		3.0	6.58	7.43	10.6	11.0
		4.0	6.57	7.57	9.8	7.7
77	Greenfield sandy loam	0.5	5.84	6.98	10.2	17.0
		1.0	6.05	7.35	10.2	16.7
		2.0	6.73	7.61	11.6	16.6
		3.0	6.73	7.52	12.5	18.2
78	Merriam sandy loam	0.5	5.95	7.32	12.2	16.4
		1.0	6.20	7.22	13.5	17.3
		2.0	6.12	7.23	15.6	18.8

4.35 to 6.75 respectively. The trees are of enormous size and of excellent color and are being top-worked to a fruitful scion.

Orchard 76 is an outstanding one, consisting of 26-year-old seedling avocado trees that were top-worked with scions of a productive strain of the Fuerte variety. Three pounds of nitrogen in the form of a complete fertilizer that includes ammonium sulfate and phosphate (no manure) has been used during the last 10 years with low sprinklers and no cultivation.

An outstanding 12-year-old avocado orchard planted to the Fuerte and Nabal varieties has received no manure for the last 3 years and 6 pounds of ammonium sulfate per tree annually and yet has shown an average annual yield of 180 pounds of fruit per tree. This orchard is on Sierra sandy loam. The pH values for the first 4 feet of soil ranged from 5.11 to 5.95. Orchards 77 and 78 are about 11 years old and are typical of a large number of orchards sampled. The trees are thrifty in appearance and are most satisfactory.

Orchards in Santa Barbara, Imperial, and Butte Counties

Soil samples from 22 orchards in the more distant counties were placed in closed containers, and the pH values were determined in the laboratory. With delayed pH tests some reservations are necessary. The data, however, are the first to be determined at the field moisture content for the soils of these areas and are enlightening. In orchard 79, which is affected by a high water table and chlorosis, the 8-year-old trees are very poor. Table 6 shows the high pH values. In contrast, no. 80 is an excellent, high-producing orchard. The 5-year-old trees in orchard 81 are stunted and poor. The soil has been heavily limed in the past. Orchards 82 and 83 are excellent. Orchards 84 and 85 are being injured by minor-element deficiencies. One of the principal effects of high pH is that of making unavailable certain of the so-called minor elements. The avocado orchard 86 was in excellent condition.

Data are given for only two of the many walnut orchards sampled. At the field moisture content the pH values are acid somewhere in the soil profile. Marked differences exist in the moisture equivalents of the soils in the two orchards. In orchard 88 the leaves showed definite symptoms of a manganese deficiency, though otherwise in good health. The trees in orchard 87 were healthy.

Orchard 89 is typical of many nitrogen-deficient orchards. The 14-year-old orchard 90 is an excellent and well cared for orchard. The 9-year-old Valencia orange orchard 91, in which a cover crop is grown each summer, is in excellent condition. Orchard 92 consists of 40-year-old trees growing in a clay loam soil; orchard 93 consists of 30-year-old trees growing in Redding gravelly loam. The moisture contents of the samples were close to the moisture equivalents.

A tract of deep clay soil in the Imperial Valley considered heretofore to be strongly alkaline gave pH values of 6.57 to 7.00 for depths of 1 to 4 feet at field moisture percentages of 25 to 30 per cent.

TABLE 6

Laboratory determinations of the pH of soils in citrus, walnut, and avocado orchards in Santa Barbara, Imperial, and Butte Counties

ORCHARD NUMBER	DEPTH IN FEET	pH OF SOIL AT FIELD MOISTURE CONTENT (IN BEAKER)	pH (1–5 SOIL-WATER RATIO)	MOISTURE PERCENTAGE	MOISTURE EQUIVALENT
Lemon (Santa Barbara County)					
79	0.5	7.06	8.17	15.3	18.9
	1.0	6.90	7.98	20.1	20.8
	1.5	7.30	8.31	22.4	19.7
	2.0	7.77	8.70	20.5	16.4
80	0.5	5.50	7.36	6.1	11.1
	1.0	6.99	7.44	8.4	9.6
	1.5	6.64	7.40	11.3	11.8
	2.0	6.80	7.14	11.8	13.2
	3.0	6.78	7.12	9.7	11.9
81	0.5	7.17	8.98	13.2	17.1
	1.0	7.21	9.00	16.9	18.3
	2.0	7.38	8.92	24.4	25.2
	3.0	8.01	9.13	29.5	24.9
82	0.5	5.21	6.01	5.2	15.9
	1.0	5.07	5.61	12.9	16.8
	2.0	5.36	5.94	15.1	14.8
	3.0	5.82	6.79	13.8	18.3
	4.0	6.80	8.12	14.4	21.0
83	0.5	5.51	6.49	4.6	14.6
	1.0	6.05	6.92	5.7	13.5
	2.0	5.44	6.38	11.6	19.1
84	0.5	7.41	8.25	19.9	28.6
	1.0	7.49	8.40	23.5	31.9
	2.0	7.42	8.33	20.7	26.8
	3.0	7.54	8.59	17.3	22.4
	4.0	7.81	8.78	13.3	16.7
85	0.5	7.68	8.01	14.0	20.4
	1.0	7.46	7.98	16.8	21.9
	2.0	7.66	7.93	19.3	19.4
	3.0	7.70	8.17	20.1	19.8
	4.0	7.60	8.07	17.0	18.0
Avocado (Santa Barbara County)					
86	0.5	5.83	6.50	6.9	15.1
	1.0	6.32	6.60	7.6	15.3
	2.0	6.08	6.44	9.3	14.2
	3.0	5.60	6.20	8.7	13.7
	4.0	5.60	6.05	10.9	13.4

TABLE 6—*Concluded*

ORCHARD NUMBER	DEPTH IN FEET	pH OF SOIL AT FIELD MOISTURE CONTENT (IN BEAKER)	pH (1-5 SOIL-WATER RATIO)	MOISTURE PERCENTAGE	MOISTURE EQUIVALENT
		Walnut (Santa Barbara County)			
87	0.5	6.69	7.21	8.2	14.3
	1.0	6.65	7.01	10.1	14.7
	2.0	6.62	7.54	11.8	13.8
	3.0	6.59	7.07	12.9	15.0
	4.0	7.53	8.72	12.8	15.7
88	0.5	6.90	8.03	20.0 ⎫	35.1
	1.0	6.80	8.19	24.0 ⎭	
	2.0	7.00	8.07	25.7	37.0
	3.0	6.82	7.89	25.9	38.5
	4.0	7.00	8.06	25.7	38.2
		Grapefruit (Imperial County)			
89	1.0	6.82	8.75	17.4	
	2.0	7.07	8.38	20.9	
	3.0	7.11	8.16	26.7	
	4.0	7.05	8.19	26.9	
90	1.0	6.57	8.52	24.6	25.1
	2.0	6.85	8.30	23.9	
	3.0	6.85	8.42	23.9	
	4.0	6.89	8.50	26.3	
		Valencia orange (Imperial County)			
91	1.0	6.84	8.25	22.5	
	2.0	6.70	8.46	22.5	
	3.0	6.40	8.59	24.3	
	4.0	6.55	8.48	28.0	
		Washington navel orange (Butte County)			
92	0.5	7.07	7.27	27.7	23.1
	1.0	7.20	7.38	22.9	22.9
	2.0	7.06	7.38	17.2	20.2
	3.0	6.91	7.46	14.2	18.3
93	0.5	6.76	7.10	15.8	17.6
	1.0	7.04	7.20	14.0	15.9
	2.0	6.02	7.32	13.8	17.5
	3.0	6.47	7.22	17.8	22.5

DISCUSSION

It is evident that irrigated agriculture need not necessarily be an alkaline agriculture. Various practices such as fertilization and soil moisture control may have appreciable effects on the pH of soils. The pH of soils in other

agricultural areas ought to be reexamined, especially in cases in which the pH values were not obtained *in situ* or immediately after sampling. Unless areas in the soil profile are acid for suitable periods in the growth of orchard trees, minor-element deficiency symptoms and other injurious effects may occur. Many soils will require further study at moisture contents corresponding more closely to those occurring in the field.

SUMMARY

The pH values of several hundred orchard soils of a wide range of soil types and locations have been determined. With few exceptions, the pH values found in soil *in situ* at various depths in orchards indicated an acid condition. When field determinations of pH were rechecked the same day in the laboratory, on the original samples stored in closed containers, it was found that storage usually, but not always, was accompanied by an increase in the pH values. Gradients in the pH values of orchard soils from the various depths may point in either or both directions.

In fertilizer trials in certain lemon orchards, the ammonium phosphate-treated soil was more acid than either the manure- or the calcium nitrate-treated soils and produced the best results. The exclusive use of manure in certain orchards was accompanied by relatively high pH values in the soil and by symptoms of minor-element deficiency in the leaves, whereas the use of ammonium sulfate as a supplement was accompanied by a reduction in the pH and by no deficiency symptoms. The application of virgin soil to an old orchard resulted in marked beneficial effects, now obtainable through the medium of certain sprays.

Many old outstanding orchards were growing in acid soils when the pH values were determined at the field moisture content. When growth was healthy, somewhere in the medium an acid condition could be found. Many orchards were successful when the pH values of the soil at the 1-5 soil-water ratio were 8.0 or higher, provided the soil moisture was kept under control and limitations were made thereby on the extent of hydrolysis.

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CHEMICAL PROPERTIES OF SOME REPRESENTATIVE SAMPLES OF CERTAIN GREAT SOIL GROUPS AND THEIR RELATION TO GENETIC SOIL CLASSIFICATION[1]

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Investigations of the chemical composition of soil colloids, particularly the SiO_2/R_2O_3 ratio of the inorganic fraction and the C/N ratio of the organic fraction, with a view to classifying the soil profile from the genetic aspect, have met with considerable although not complete success. The amphoteric properties of the colloidal fraction as revealed by its neutralization curves with acid and base have also been employed to characterize the genetic soil-forming processes and serve as a basis of classification.

In no case on record have the accurate C/N ratio of the colloids and the SiO_2/R_2O_3 ratio of the colloidal fraction been compared to the neutralization curve to find the degree of agreement of this factor with, or of its deviation from, the other factors of classification. It is the purpose of this investigation to find whether such a relationship does exist, and, if it exists, whether the agreement is sufficient to warrant suggesting a classification based on the neutralization curve alone.

REVIEW OF LITERATURE

Leighty and Shorey (15) working with 63 profiles representing most of the great soil groupt found that the C/N ratio is variable within a single profile but, with few exceptions, is highess in the surface soil and becomes less at the lower levels.

Anderson and Byers (2) found that there is an essential difference in the C/N ratio of the organic matter of the soil groups. There was no definite relationship between the C/N ratios of the different soil groups, but the ratio decreased with depth of the horizons in a particular profile.

Jenny (13) has established some very interesting facts regarding the C/N ratios in well-drained upland soils from the western part of Colorado to the eastern shore of New Jersey along the isotherm that includes average annual temperatures ranging from 51° to 53°F. Along this isotherm he found fairly constant C/N ratios, averaging 11.6 for grassland soils and 10.9 for forest soils.

Lunt (16) has reported C/N ratios as wide as 24 to 1 in forest soils of the New England States. He also substantiated the fact that the C/N ratio might vary appreciably from season to season. Because of loss of pentosans and celluloses, which are high in oxygen and accumulation of lignins and synthesized cellular material, which are high in carbon, the percentage of carbon increases as decomposition progresses.

Brown and Byers (7) have shown that in both soils and colloids the C/N ratio generally decreases with depth, although some exceptions were found. The quantities of organic matter at lower levels were in some instances so small as to make the data unreliable, particularly when the carbonate content was high.

Hough and Byers (12) in their work on the colloidal fraction of some Hawaiian soil profiles found widely different and often erratic ratios for the carbon and nitrogen in the colloids where the nitrogen and carbon were directly determined on the colloidal fraction and the ratio calculated. The ratios were found to vary from below 10 to well over 40.

Holmes, Hearn, and Byers (11) also found widely varying ratios for the colloidal fractions of the Norfolk and related soil series.

Anderson and Byers (1), Brown and Byers (6), and Byers, Alexander, and Holmes (9) studied the character of the colloidal materials in the profiles of certain major soil groups. They classified three major soil-making processes—calcification, podzolization, and lateralization—by the character of the colloidal materials developed. The information concerning the lateritic colloidal fraction led these investigators to conclude that the soil colloids of this group were sufficiently different to distinguish them from the chernozem, prairie, and podzol colloids. Each soil group in turn differs fundamentally from the others, and there is a colloidal chemical basis for the physical characteristics of the soil as these are manifested in the field. The summary of the work of Holmes and Edgington (10) is in every way comparable to results obtained by Byers and his co-workers.

Anderson and Byers (3) conclude from their work that the neutralization curves of the colloids from the great soil groups vary sufficiently to differentiate each group. The colloids of the lateritic soils have much weaker acid qualities than those of the chernozem soils, and their titration curves are markedly different. The prairie and the gray-brown podzolic groups have titration curves intermediate in character between those of the pedocal and lateritic soils. The curves of the colloids of true podzols are widely different for adjacent horizons of a particular profile, and corresponding horizons of different profiles show wide variation in acidic as well as other chemical qualities. Their neutralization curves, however, do not indicate the activity of the basoid fraction, since the colloids were not titrated with acid.

Mattson (18, 19, 20, 21, 22, 23, 24) has investigated thoroughly the use of a neutralization curve to characterize the podzol profile. He defined a number of terms. The pH of exchange neutrality, or the equiionic point as he later (22) redefined it, is the pH at which the unsaturated soil colloid combines with an equal number of the anions and cations of a neutral salt and, therefore, does not affect the pH of the solution. This characteristic was found to fall along a linear gradient, in the podzol profile, being highest in the C horizon, lower in the B, and lowest in the A horizon. The base-combining capacity at pH 7.0 was found to have two maxima, one in the A_0 horizon and the other in the B horizon. Mattson (19) concludes that a soil profile can be characterized by the neutralization curves of the colloidal fractions from the horizons of each profile and that the curves so obtained are in agreement with his theory of isoelectric weathering.

EXPERIMENTAL PROCEDURE

Soils of 10 series representative of certain of the great soil groups, as indicated in table 1, were obtained. The profile descriptions of these soils may be found in another publication (26). From each of the 10 soils, samples representative of two horizons, an A and a B, were investigated.

A 2400-gm. sample of 2-mm. mesh soil from each horizon was dispersed in 12 liters of distilled water in a 12-gallon crock by the use of a special propeller mixer. The sample was mixed for 10 minutes, allowed to stand for 68 minutes, and the surface 10 cm. was syphoned off through a cloth strainer. This was repeated until sufficient colloids had been obtained or until no more colloids

TABLE 1

Geological origin, zonal category, precipitation, and mechanical composition of soils of 10 series representative of certain great soil groups

SOIL NUMBER AND HORIZON	SOIL SERIES	GEOLOGICAL ORIGIN OF PARENT MATERIAL	MEAN ANNUAL PRECIPITATION*	ZONAL CATEGORY	DEPTH	SAND	SILT	CLAY	CLASS
			inches		*inches*	*per cent*	*per cent*	*per cent*	
1A	Ephrata	Alluvial	8.38	Northern gray desert	0–10	67.17	24.52	8.31	Sandy loam
2B					10–36	66.13	25.81	8.06	Sandy loam
20A	Ritzville	Loessial	10.60	Brown	0–12	28.80	56.40	14.80	Silt loam
21B					12–24	24.12	48.69	27.19	Clay loam
6A	Garrison	Glacial terrace	16.62	Prairie	0–8	38.06	43.26	18.68	Gravelly loam
7B					8–18	36.54	44.61	18.85	Gravelly loam
18A	Palouse	Loessial	20.51	Prairie	0–14	16.14	52.18	31.68	Silty clay
19B					14–26	14.39	54.55	31.06	Silty clay
22A	Barnes	Glacial drift	20.93	Chernozem	1–12	28.81	42.21	28.98	Clay loam
23B					16–28	27.77	32.01	40.22	Clay
8A	Helmer	Loessial	21.16	Gray-brown forest	0–14	22.12	58.21	19.67	Silt loam
9B					14–25	21.20	54.40	24.40	Silty clay loam
3A	Lynden	Glacial outwash	35.25	Yellow-brown†	0–8	55.71	28.94	15.35	Sandy loam
4B					8–28	82.44	12.05	5.51	Sand
16A	Spanaway‡ (forest)	Glacial outwash	44.54	Prairie or black-brown†	0–16	75.60	15.60	8.80	Gravelly sandy loam
17B					16–30	78.24	17.13	4.63	Gravelly sandy loam
32A	Greenville	Residual	55.78	Lateritic	0–3	80.2	10.80	9.00	Sand
34B					24+	73.20	3.00	23.80	Sandy clay loam
10A	Rainier§	Glacial	76.67	Podzol	1½–5	74.80	18.00	7.20	Gravelly sandy loam
11B					5–18	69.58	22.61	7.81	Gravelly sandy loam

* Climatological Data of U. S. Weather Bureau.
† Designation of Nikiforoff (25).
‡ At present under forest vegetation which, it is indicated by Nikiforoff, is forcing its way on the prairie islands.
§ Local name given because of proximity to Mt. Rainier, Washington.

were extractable. The supernatant liquid contained mineral colloidal particles of 5μ and less, according to Stokes' equation for the settling rate of particles through a suspension. Particles of organic character larger than 5μ would undoubtedly be included in this separated colloidal fraction. The liquid was then passed through the Sharples centrifuge rotating at 16,000 r.p.m., and the
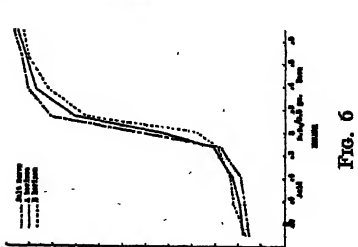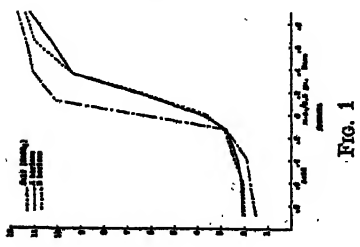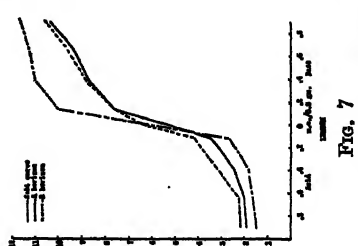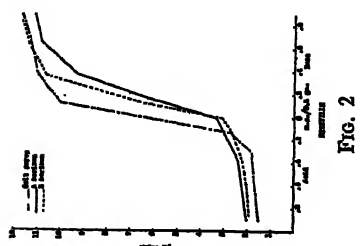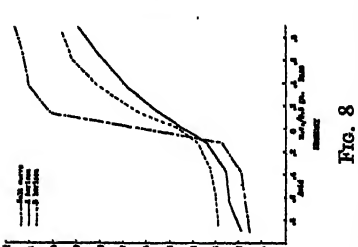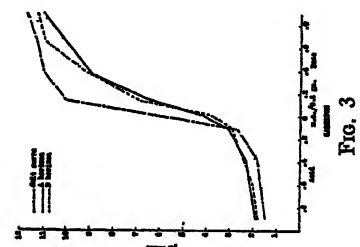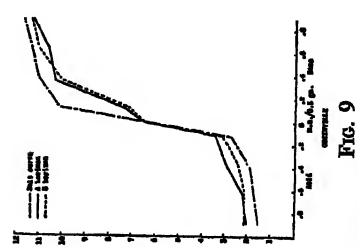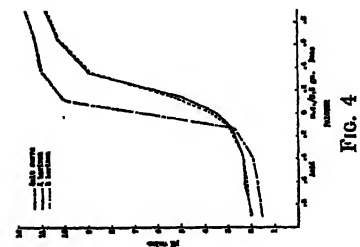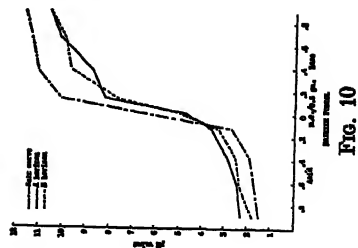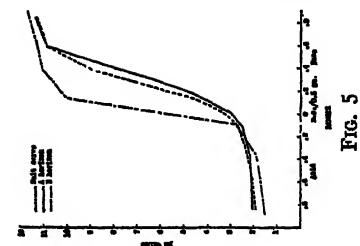
FIGS. 1-10. NEUTRALIZATION CURVES OF THE SOILS OF 10 SERIES

colloids were collected in the centrifuge bowl. The colloids were dried in an oven at 68°C. and then ground to pass through a 40-mesh seive.

Unsaturation was accomplished by leaching 15 gm. of colloids with 0.05 N HCl until all exchangeable cations were removed. Unsaturation was determined by testing a portion of the leachate for calcium by the oxalate method. The HCl was then removed by leaching with H_2O until free of chloride.

In determining the neutralization curves and the pH of exchange neutrality, 7.5 cc. of a 0.0227 N solution of $CaSO_4$ was added to each 0.5-gm. sample of unsaturated colloid. Eight samples from each soil horizon were used, 3, 9, 15, and 21 cc. respectively of 0.0424 N H_2SO_4 being added to each of four samples to attain the maximum effect on the acid side, and corresponding volumes of 0.0418 N $Ca(OH)_2$ to attain the maximum effect of the base. The samples were made up to 40 cc. with distilled water in each case and allowed to stand for 14 hours with frequent shaking. The pH was determined by the use of the glass electrode apparatus. The data are indicated in figures 1 to 10.

From each horizon of every soil a 50-gm. sample of 2-mm. mesh soil was used for a mechanical analysis by the improved Bouyoucos method (5). The data are indicated in table 1.

On a 1-gm. sample of unleached colloid, the amount of total nitrogen was determined by the standard Kjeldahl method (4); the total carbon, by the wet combustion method (4); and the carbonate carbon, by the A. O. A. C. method (4).

RESULTS AND DISCUSSION

Soil texture

The textural characteristics of the various soils (table 1) indicated, in general, wider variations between soils than zonal soil-forming processes could logically explain. The reason for this variation is to be found in the differences in the geological origin of the parent material, particularly the mode of deposition.

Certain investigators (27) have indicated that with parent materials of similar mechanical and chemical composition textural differences may reflect the zonal soil-forming processes. On the other hand, texture may modify the soil climate sufficiently to alter the level of equilibrium in these processes and the rate of approach of this equilibrium. For example, the extremely coarse textured Garrison soil exhibits no carbonate accumulation layer within the solum although it is developing under a mean annual precipitation of only 16.62 inches, whereas the coarse texture of the Spanaway soil has been indicated by Nikiforoff (25) as contributing to the maintenance of prairie islands within a region otherwise dominated by forests.

Further consideration of the textural variations will be given in the discussion of the organic matter relationships.

Organic matter and C/N relationships

Table 2 presents the results of complete nitrogen and carbon determinations on the clay fractions and on the whole soil and the C/N ratios calculated from

these determinations. The carbon contents and the C/N ratios for the whole soil, as determined by Vandecaveye and Katznelson (26), have been listed to enable more complete evaluation of the data. One of the most striking relations indicated is the tendency for the organic matter to concentrate in the clay

TABLE 2

Organic matter relationships of the soils

SOIL		WHOLE SOIL*			CLAY FRACTION			RATIO OF %'s C†	CLAY	CLAY C‡
		C	N	C/N	C	N	C/N			
		per cent	per cent		per cent	per cent			per cent	per cent
1A	Ephrata	0.989	.063	15.77	4.05	.415	9.76	4.10	8.3	0.336
2B		0.873	.041	21.58	2.42	.393	6.16	2.77	8.1	0.196
20A	Ritzville	2.192	.148	14.81	3.10	.370	8.37	1.41	14.8	0.641
21B		0.826	.065	12.63	1.05	.219	4.79	1.27	27.2	0.653
6A	Garrison	3.902	.226	17.25	8.54	.480	17.79	2.19	18.7	1.329
7B		1.200	.109	11.00	3.79	.309	12.26	3.16	18.9	0.724
18A	Palouse	2.796	.164	17.02	3.16	.247	12.79	1.13	31.7	1.002
19B		1.087	.047	23.06	1.22	.090	13.15	1.12	31.1	0.662
22A	Barnes	4.557	.372	12.25	5.36	.544	9.85	1.17	29.0	2.236
23B		1.394	.009	14.08	2.16	.124	17.4	1.60	40.2	0.869
8A	Helmer	1.730	.077	22.56	3.61	.161	22.02	1.83	19.7	0.810
9B		0.749	.032	23.15	1.43	.079	18.10	1.91	24.4	0.349
3A	Lynden	1.342	.054	24.80	5.72	.393	14.55	4.26	15.4	0.881
4B		1.288	.041	31.76	2.51	.301	8.34	1.95	5.5	0.138
16A	Spanaway	8.979	.693	22.94	14.42	1.676	8.60	1.61	8.8	1.269
17B		0.748	.221	29.80	7.20	.....	.....	9.63	4.6	0.331
32A	Greenville	1.729	.072	24.06	5.36	.403	13.30	3.10	9.0	0.482
34B		0.466	.023	23.10	3.80	.229	16.59	8.15	23.8	0.904
10A	Rainier	1.415	.030	47.01	5.35	.225	23.78	3.78	7.2	0.385
11B		0.732	.014	50.69	7.48	.296	25.27	10.22	7.8	0.583

* Data taken from publication of Vandecaveye and Katznelson (26).

† Calculated by quotient of $\dfrac{\% \text{ C in clay}}{\% \text{ C in whole soil}}$.

‡ Clay C = % clay × % C in clay.

fraction as the latter was separated. The ratio of the percentage of carbon in the clay fraction and in the whole soil shows a range from 1.12 in the Palouse to 10.22 in the Rainier podzol. The tendency is for the higher ratios to occur in soils with the lower clay contents.

Even more interesting is the comparison of the individual soils with respect to the carbon contents of the clay fraction and the whole soil. The Ritzville soil, which has over twice as much total carbon as that of the Ephrata in the A horizon, has less carbon in the clay fraction, whereas in the B horizon, with an approximately equal amount of total carbon in both samples, the Ephrata has over twice as much carbon in the clay fraction. This differential behavior of the organic fractions in the A and B horizons is found also in the C/N ratios not only of the total organic matter but also of the clay-organic matter.

The Garrison and Ritzville soils exhibit a variation in the organic carbon content of their colloidal fractions far greater than one would expect on the basis of the difference in total annual rainfall. Explanation for this marked variation must be sought in a factor not made evident by the mechanical analysis, for which only the 2-mm. mesh material was used, notably, the gravel content of the Garrison soil. Fully half of the Garrison profile is made up of stones and gravel. Consequently, the organic matter produced must remain in the smaller mass of fine material, thereby resulting in a higher concentration of organic matter in the capillary active soil phase. During seasons of high moisture (spring and early summer), this soil produces an excellent growth of grass vegetation; however, in July and August when rainfall is light, vegetative growth is stopped by the dryng out of the soil. This severe desiccating effect might be a factor in preventing bacterial decomposition, because of both the cessation of activity of the microflora and the irreversible aggregation of the organic matter, thus contributing further to the much higher organic matter content of the Garrison soil.

Proceeding further up the moisture scale to the Palouse soil, still with the same seasonal distribution of precipitation as that of the Ephrata, Ritzville, and Garrison, a decrease is found in the carbon and organic matter content from the level of that found in the Garrison. The Palouse soil supports a more luxuriant vegetative growth, but because of its heavier texture and greater moisture-holding capacity, the organic matter is distributed through a greater mass of capillary active soil phase and also a more extended period of bacterial activity is permitted.

As a factor for the difference in organic content of the Palouse and Barnes colloids, total rainfall is hardly significant. If we investigate the nature of its distribution, however, we find that during May, June, July, August, and September the rainfall of the area in which the Barnes series is located is greater than the average monthly value, June having the greatest monthly precipitation. Under rainfall conditions of the Palouse region the precipitation during November, December, January, and February exceeds the average monthly value. As a result of this distribution of precipitation, the moisture is more effective in percolation processes within the Palouse profile at a time when the vegetation is relatively inactive, giving rise to a soil resembling the prairie type of Marbut; whereas in the Barnes, which is a typical chernozem, the precipitation is more effective in stimulating the vegetative growth of the

grasses and less effective in the percolation processes. From the work of Weaver and his co-workers (28), it may be inferred that there will be a tendency for a greater concentration of a more fibrous root system in the surface layers of the Barnes, whereas in the Palouse the roots penetrate the greater depths to which moisture has percolated, resulting in a less concentrated root system in the surface layers. This combination of circumstances may explain the variations in the organic contents of the Barnes and Palouse colloids and of the respective whole soils.

The Helmer soil, unlike the others previously discussed, is found under a coniferous forest vegetation, with slightly more precipitation than the Palouse series but with a similar distribution of precipitation. Its total carbon content, although less than that of the Palouse in the whole soil shows a similar percentage in the clay fraction, thus indicating that a greater percentage of the organic carbon is in the colloidal condition within the horizon. The absence of an appreciable quantity of fine rootlets in the Helmer and its prominent duff layer of pine needles which serves as the reservoir of infiltrating colloidal organic matter may be responsible for this condition.

In grouping the Spanaway, Lynden, and Greenville soils, consideration is given to the more moderate temperature relations which distinguish the climate under which this group was formed. The Spanaway and Lynden from western Washington with its mild marine climate and the Greenville from northern Florida with its subtropical rain-forest climate are developing under forest vegetation, the Washington soils under mixed conifers, and the Florida soil under the longleaf-loblolly pine complex. The precipitation in western Washington, like that in eastern Washington, occurs principally during November, December, January, and February, whereas that in Florida occurs principally during June, July, August, and September.

With these points in mind, a comparison of the organic contents of the colloidal fractions from these soils shows a direct reflection of the climatic factors.

The Spanaway sample, for which the data are presented in this paper, is regarded as originally having developed under a grass vegetation but as now developing under a stand of mixed conifers which has invaded the prairie island. A discussion of this "biological battle" is given by Nikiforoff (25). Although the rainfall is higher than normal for the typical prairie region, the biological pressure is lowered by the physical character of the parent material. The Spanaway prairie and its adjacent forested areas are found upon loose and porous fluvioglacial deposits. These deposits usually extend to considerable depth and are composed of unassorted gravels, pebbles, and sands. In addition, the organic matter which becomes concentrated in the relatively small mass of finer textured capillarily active material becomes strongly desiccated during the dry months of June, July, and August, and, consequently, may become somewhat irreversible, thereby contributing to a comparatively high level of organic matter at which equilibrium is established. The Lynden, on the other hand, having a greater reservoir capacity for moisture and thereby

permitting a more extended period of microbial activity, shows a decided decrease in the organic content of the colloidal fraction, a decrease which continues into the Greenville with its more nearly optimum conditions for microbial activity. Thus the trio of soils brings out again that the supraterrestrial climate cannot be absolute in its designation of the organic level in the soil but must be correlated with the soil climate which results from its operation.

In all the soils discussed so far, the organic content in the colloidal fraction from the A horizon is greater than in that from the B horizon. In the Rainier podzol, however, this condition is reversed. The colloid from the surface horizon, bleached in character, contains much less organic matter than the colloid from the B horizon. This soil, which was produced in a region of vertical zonation in the Mt. Rainier area of the Cascade Range, shows results typical of the morphological data reported elsewhere (14, 17) for the differences between the bleached A_2 and the B horizons. It will be seen later in the discussion of the neutralization curves that its chemical properties do not follow exactly those of the mature podzol found in the eastern part of the United States, but as has been pointed out by Joffe (14), the vertical zonation counterparts of the horizontal zonal soils are not always in perfect agreement with respect to their inherent chemical properties, although they may resemble each other morphologically in all details.

C/N ratio

The ratio of the carbon to nitrogen bears its greatest significance in classification in its relationship to the soil groups. The samples of Ephrata, Ritzville, and Palouse soils, formed under more arid conditions, show a narrow C/N ratio, and as the rainfall increases, such soils as the podzols show a higher ratio. The increase in the C/N ratio in relation to increased rainfall, insofar as the colloidal fractions are concerned, is in keeping with Mattson's theory of isoelectric precipitation, in which he points out that the soils of a high pH maintain a colloidal organic matter of a narrower C/N ratio than those of a low pH. As will be brought out in the discussion of the neutralization curves, this C/N ratio does express itself in the acidoid/basoid relationships.

Of particular interest is the fact that the C/N ratios of the whole soil are in nearly all instances wider than those of the clay fraction (table 2).

Neutralization curves

The neutralization curves determined on the colloidal fractions of the soil samples are the focus of this investigation. It is to be noted from table 3 that there is no definite gradient of the equiionic pH values of the horizons within a profile but there is a measureable difference between soil groups. Soils formed under arid to semiarid weathering conditions; namely, the Ephrata, Ritzville, Garrison, Palouse, and Barnes, show a lower equiionic pH than do those formed under more humid conditions. The variation from pH 3.0 for the surface horizon of the Ephrata series to pH 4.1 for the surface horizon of the Helmer

indicates the relationship that exists between these two soil groups. The profiles of the soils formed under arid to semiarid conditions of weathering show a variation in the equiionic point within the limits of pH 2.6 to pH 3.2, whereas the Helmer, Rainier, Spanaway, Lynden, and Greenville soils, which have developed under podzolic to lateritic weathering processes, show a varia-

TABLE 3

Chemical ratios and equiionic pH values of the colloidal fractions of the soils

soil		SiO_2/R_2O_3*	SiO_2/Al_2O_3*	equiionic pH	BASE-BINDING CAPACITY†
					m.e./100 gm.
1A	Ephrata	4.49	5.70	3.0	44
2B		3.94	4.89	2.9	44
20A	Ritzville	4.36	5.50	3.2	44
21B		3.60	4.64	2.6	32
6A	Garrison	3.56	4.47	3.2	36
7B		2.75	3.46	3.2	28
18A	Palouse	3.09	4.08	2.8	52
19B		2.99	3.96	3.0	50
22B	Barnes	5.72	7.49	2.7	66
23B		4.16	5.61	2.8	52
8A	Helmer	3.67	4.61	4.1	12
9B		3.01	3.81	3.2	20
3A	Lynden	2.04	2.74	4.2	20
4B		1.96	2.47	5.3	16
16A	Spanaway	1.75	1.99	3.7	80
17B		1.96	2.38	4.0	44
32A	Greenville	1.96	2.32	5.3	19
34B		1.47	1.77	5.2	16
10A	Rainier	4.35	5.27	4.0	19
11B		2.54	3.09	3.9	20

* Chemical determinations made by Blaine L. Bishop.
† From neutralization curves at pH 7.0.

tion within the higher limits of pH 3.2 to pH 5.3. The increase is evidently due to the greater activity of the basoid residue in soils formed under more humid conditions.

According to the values expressed in tables 2 and 3, the neutralization curves for the Ephrata (fig. 1) and Ritzville soils (fig. 2) would be expected to be very similar. The silica/sesquioxide ratios, the silica/alumina ratios, and the col-

loidal organic matter contents are very similar for the two soils. The neutralization curves for these soils show a marked difference between the salt solution curve and those for the colloid. The region of greater variation is in the buffer capacity against bases. This phenomenon indicates a highly active acidoid fraction. In view of the higher organic matter content of the colloid from the A horizon one might expect a lower equiionic point in that horizon were it not for the dominance of total activity by the inorganic fraction.

The neutralization curves of the Garrison series (fig. 3) are very similar to those of the Ephrata and the Ritzville. This similarity is in keeping with the close relationship of the nature of the clay fractions of these soil groups. The variation between the two horizons in the Garrison is insignificant in spite of the significantly greater content of carbon in the colloidal clay fraction of the A horizon. The greater aridity of the soil climate due to the gravelly texture of the Garrison has probably contributed to the inactivity of the organic fraction. This inactivity is particularly evident in the low base-binding capacity of the Garrison samples.

The curves of the Palouse and Barnes colloids (figs. 4 and 5) resemble very markedly those of the Ephrata, Ritzville, and Garrison with the organic fraction of the Barnes playing a more prominent role in the acidoid properties. The shape of the curves for both horizons shows the uniformly low buffer capacity toward acid that one expects for the semiarid soils in which extensive weathering has not occurred. The significantly wider silica-sesquioxide ratio and the higher organic acidoid content of the Barnes are reflected in the fact that its equiionic pH values are the lowest and its base-combining capacity at pH 7.0 the highest among the pedocalic soils in this study.

The Helmer soil (fig. 6), which morphologically resembles a gray-brown podzolic type of soil, shows in its colloidal fraction the most weakly active buffering capacity of the entire group of soils studied. The A horizon of the Helmer series has a neutralization curve with the soil colloid which is closely analogous to that for the salt solution. In the B horizon the deviation from the solution curve, though a little more pronounced, is not significantly greater than that of the A horizon. The coniferous vegetation, the moisture and temperature relationships, and the chemical characteristics are favorable for the podzolic soil-forming process but, morphologically, are not very strongly expressed. In table 3, the silica/sesquioxide ratio and the silica/alumina ratio are roughly comparable to those values for the pedocal soil group. The high equiionic pH of the A horizon reflects, however, a much less active acidoid fraction than is characteristic of the pedocal soil group.

The colloidal fraction of the Lynden series (fig. 7) shows a fairly high equiionic pH in the A horizon and a still higher in the B horizon. This value in the B horizon is higher than in any of the soils previously discussed. Within the profile itself, the lower buffer capacity of the colloids against acid in the A horizon indicates a higher activity of the acidoid fraction, an activity which may reside in the organic fraction. The relatively narrow C/N ratio in the organic

fraction, however, undoubtedly contributes to the comparatively low buffer capacity against bases. The fairly high buffer capacity of the B horizon against acid is indicative of the narrower acidoid/basoid ratio of the inorganic portion of the colloidal complex. The B horizon of the Lynden also has a relatively low value for the humic acidoid fraction which, with a narrow C/N ratio in its make-up, accordingly results in a low buffer capacity against bases.

The Spanaway series (fig. 8) exhibits an extremely high buffer capacity against bases in spite of its low silica-sesquioxide ratio. The explanation of the behavior lies in the extremely large quantity of organic acidoid although of comparatively narrow C/N ratio. Strangely enough, this large quantity of organic acidoid still permits a rather complete expression of the inorganic basoid properties on the acid side of the equiionic point. That the Spanaway should exhibit such strong basoid properties and possess such a low silica/sesquioxide ratio was somewhat of a revelation, since the area had been tentatively classified (17) as an intrazonal prairie in the gray-brown podzolic zone. Nikiforoff (25) says that the West Coast region has an independent zone of its own; its soils cannot be considered as members of any of the definitely established great soil groups. He suggests a possibility of a general trend of the soil-forming processes along the lines of laterization. The data concerning the silica/sesquioxide ratios and neutralization curves would lead one to suspect that the soil-forming processes in both the Lynden and the Spanaway may be more lateritic than podzolic.

Proceeding now to a truly lateritic soil, the Greenville from Florida (fig. 9), we find the neutralization curves indicating the strong basoid properties of the colloidal fraction. The equiionic pH is 5.3 in the A horizon and 5.2 in the B horizon. At the same time the base-combining capacity has a low order of magnitude typical of lateritic soil colloidal material. The appreciable content of organic acidoid counteracts to some extent the basoid activity on the acid side of the equiionic pH.

The Rainier podzol (fig. 10) was only recently observed morphologically and has never been thoroughly investigated. The profile is shallow (18 inches) and was developed under severe conditions of weathering, notably, wide extremes of temperature and heavy precipitation, and is apparently not fully mature. All morphological characteristics indicate this profile to be a true podzol. The neutralization curves do not show the typical high buffer capacity against bases for the A horizon. The silica/sesquioxide ratio for the A horizon is approximately only half that observed for the colloidal fraction from the A horizon of Lakewood fine sand as reported by Joffe (14) but is of the same order of magnitude as that reported by Anderson and Byers (3) on two mature podzols from Michigan and one from Maine. The latter workers also found in one case, the Trenary series, a low buffer capacity against bases in the A horizon. A more detailed examination of the colloidal fraction might reveal the presence of inactive silica in the colloidal state, which may contribute to the wide silica/sesquioxide ratio without appreciably increasing the acidoid activity.

CONCLUSIONS

The interpretation of the neutralization curves for zonal classification of a particular soil series elicits interesting information. From the material herein presented, the small differences which distinguish one series from another do not show in sufficient magnitude on the neutralization curve to serve as an absolute index in classification. The more pronounced differences, however, are amplified in the neutralization curve to such an extent that certain factors can be logically drawn to aid in classification. The factors of classification, such as C/N ratios, were found to express themselves, not individually, but through an integrated effect in altering the shape of the neutralization curve.

The soil texture was recognized as an especially important item in determining the shape of the neutralization curve for the Spanaway and Garrison soils, inasmuch as it resulted in a stabilization of organic matter and, consequently, a larger proportion of organic acidoid was maintained.

In the light of the present investigation the shape of the neutralization curve revealed to a great extent the part which the colloidal organic matter may have in modifying the acidoid/basoid relationships and the importance of its consideration in the net activity of the soil colloidal material.

A striking relationship is shown in the comparison of the total carbon and the C/N ratios in the whole soil and the corresponding values in the extracted clay fraction. In general, there is an apparent accumulation of the organic fraction in the extracted clay as shown by the ratio of the percentages of organic carbon and by a comparison of total carbon in the soil with clay carbon as expressed in table 2. At the same time a definitely narrower C/N ratio is found for the organic matter in the clay fraction when this value is compared with the C/N ratio in the whole soil. Both of these relationships should be kept in mind in evaluating the acidoid-basoid activities in the whole soil when neutralization curves of the clay fractions are used to indicate these activities.

The effect of the colloidal organic matter on the shape of the neutralization curve was in modifying the expression of the acidoid-basoid properties of the inorganic fraction. It is this integrated effect of the colloidal organic fraction and the colloidal inorganic fraction that makes either factor alone an ineffective designation of soil characteristics.

The neutralization curve with the equiionic pH as a point on that curve, as recently defined by Mattson (23), has been found to be an expression of the difference in the weathering process between the pedocal and pedalfer soil groups. It is a function of the total acidoid/basoid relationships in the colloidal complex. The uniformly lower equiionic pH of the pedocal group is due to the relatively high activity of the inorganic component to the extent of dominating the colloidal complex. In the pedalfer group the more active organic acidoid fraction counteracts the inorganic fraction and is reflected in the shape of the neutralization curves and in the equiionic pH.

The base-binding capacity at pH 7.0, as obtained from the neutralization curves, delineates the pedocalic and pedalferic soil groups. In general, this

value is high in the pedocalic soils and relatively low in the pedalfers, except for the Spanaway, in which the exceedingly high organic acidoid content resulted in a high base-combining capacity, although the SiO_2/R_2O_3 ratio was definitely pedalferic.

SUMMARY

A study was made to determine whether the neutralization curves of a soil, after the method of Mattson, could be used to classify the soil profile. Factors of classification including soil texture, organic matter and C/N relationships, and silica/sesquioxide ratios were determined to measure the effective information that could be interpreted from the neutralization curve.

The percentage of organic carbon in the whole soil was smaller, in general, than that in the clay fraction.

The C/N ratio of the organic matter in the clay fraction of the pedocal group is much narrower, in general, than that of the pedalfer group.

The silica/sesquioxide ratios bear a close relationship to the activity of the inorganic acidoid fraction in delineating the shape of the neutralization curve, but the total acidoid/basoid ratio of the colloidal complex, due consideration being given to the organic acidoid, is probably the most decisive factor in determining the neutralization curve.

The entire curve considered as a unit indicates the type and extent of the weathering process, whereas the equiionic pH, though it is uniformly lower in the pedocals than in the pedalfers, is not an all-inclusive measurement of the acidoid/basoid ratio.

The base-binding capacity at pH 7 reflects the total active acidoid fraction in the colloidal complex but does not bear a linear relationship to the different soil-weathering processes.

The Lynden and Spanaway series from the Pacific Coast, which have been designated as belonging to the gray-brown podzolic group and the prairie group, respectively, are shown in the present investigation to have assumed attributes of lateritic soils.

The neutralization curves adequately measure prominent differences in the acidoid/basoid ratio and are a reliable basis for classifying soils into large groups such as pedocals and pedalfers and, with proper consideration of other soil attributes, may also be used to delineate the climatic zonal soil groups.

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DETERMINATION OF BORON IN SOME SOILS OF ILLINOIS AND GEORGIA[1]

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Previous determinations of boron in soils have been chiefly limited to the water-soluble and acid-soluble forms of this element. The results obtained have not correlated well with the response of crops to fertilizers containing boron (3). The responses to the application of boron have been positive on certain soils in Georgia and negative on others (7). Boron deficiencies on apple trees have been reported from Georgia (14) and strongly suspected in Illinois. These results suggest the need for further investigation of the subject. Methods previously used for the determination of both available and total boron in soils are not altogether satisfactory. This paper presents modifications of previously used methods and the results obtained on certain important soil types of Illinois and Georgia.

TOTAL BORON

Both volumetric and colorimetric methods have been used for the determination of boron in soils. In the former method boric acid is titrated as a monobasic acid after the addition of glycerol, mannite, or a similar compound. A laborious alcohol-distillation procedure is necessary to separate the boron from interfering substances present in soils and the low sensitivity of this test is also objectionable. A study of the titration method using mannite and several concentrations of sodium hydroxide indicated that amounts of boron as small as 0.02 mgm. could not be reliably titrated. A downward drift in pH observed on freshly boiled distilled water but not on ordinary distilled water indicated that absorption of carbon dioxide during titration was responsible for inconsistencies at a low concentration of boron. In the colorimetric determinations of boron, the use of turmeric and of quinalizarin has been relatively successful. Table 1 reports the method used and the results obtained by investigators who have made boron analyses on soils. Fractions determined have been water-soluble, acid-soluble and total, the last being limited to a few determinations.

The procedure for total boron in soils involves a fusion and separation as well

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as the final determination.   Potassium hydroxide was found most satisfactory for the fusion, because a soil fused with KOH can be digested quickly in a small amount of water, whereas if sodium carbonate, sodium dihydrogen phosphate, or other agent is used, the digestion is much more complicated.   Nickel crucibles were used in preference to platinum because of the action of hot KOH on the latter.   The KOH was added to the soil in solution rather than as a powder.

Boron may be separated from interfering substances in the soil by distillation as $(CH_3)_3BO_3$ in acid solution.   The distillation and other steps in the analysis

TABLE 1

Results of analyses of soils for water-soluble, acid-soluble, and total boron as reported by various investigators

INVESTIGATOR	LOCATION OF SAMPLES	METHOD USED		BORON REPORTED
		Extraction	Determination	
				p.p.m.
Askew, Thomson, and Chittenden (1)	New Zealand	Acid	Turmeric paper	0.05 to 0.75
Berger and Truog (3)	Wisconsin	Water	Quinalizarin	0.3 to 2.0
		Acid		0.2 to 5.2
		Na$_2$CO$_3$ fusion		10 to 17
Cook and Millar (4)	Michigan	Acid	Mannite with 0.05 N NaOH	0.37 to 2.05
Eaton and Wilcox (5)	California	Various	Mannite with 0.023 N NaOH	0.06 to 23.31
Ferguson and Wright (6)	Ontario	Water	Spectrographic	0.10 to 0.63
Kelley and Brown (8)	California	Water	Mannite with NaOH*	0.3 to 21.0
Robinson, Whetstone, and Byers (11)	Various	Acid NaH$_2$PO$_4$	Mannite with 0.023 N NaOH	1.0 to 45.5 6.4 to 66.0
Rogers, Gall and Gaddum (12)	Florida	......	Spectrographic	10 to 100
Scott and Webb (13)	California	Water	Turmeric paper	0.16 to 0.93
Woodbridge (15)	British Columbia	Acid	Mannite with 0.02 N NaOH	0.09 to 10.22

* Normality not reported.

must be carried out in containers free of boron.   Corning No. 728 and Kavalier glassware have been found satisfactory.   About 90 per cent of the boron is removed from the soil by distillation, but this procedure is too laborious to be practical.   A separation involving the use of concentrated sulfuric acid resulted in a satisfactory agreement between replicate determinations and in sufficient recovery of boron added to the soil, as shown in table 2.

After the KOH fusion, the soil mass was first taken up in water and then digested in $(1 + 3)\,H_2SO_4$.   More dilute H_2SO_4 for the extraction resulted in the

precipitation of silicic acid when 98.5 per cent by weight H_2SO_4 was added in the final steps of the determination.   When $(1 + 3)$ H_2SO_4 is used in the initial steps of the procedure, only minute quantities of silica are in solution and no precipitation occurs during the final addition of acid.   The solutions were made to volume before filtration.   In some soils when the sulfuric acid is added, a pink or brown color is produced as a result of the presence of manganese in a high state of oxidation.   Ferrous ammonium sulfate was added to reduce the manganese and other oxidizing substances that interfere in the determination. To eliminate the possibility of volatilization of the boron, the solutions were

TABLE 2

Efficiency of the acid-extraction method in recovering boron added to soil samples

SOIL TYPE	BORON ADDED	BORON RECOVERED	
	mgm.	*mgm.*	*per cent*
Decatur clay loam....................	.010	.012	120
Norfolk sandy loam..................	.010	.010	100
Cecil sandy clay loam................	.020	.018	90
Cisne silt loam......................	.010	.009	90
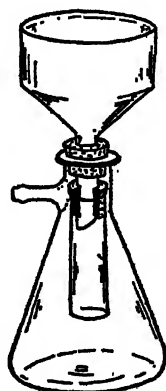
FIG. 1. FILTERING APPARATUS USED IN THE DETERMINATION OF TOTAL BORON IN SOIL

cooled in a water bath as the concentrated sulfuric acid was added.   The total volume for 1 gm. of soil was restricted to from 30 to 35 cc., and a 10-cc. aliquot was taken from the supernatant liquid or from the filtrate for the determination. The determinations were carried out by means of the photoelectric colorimeter, as described recently by the authors (10).   Details of the separation and determination follow.

One gram of 100-mesh, air-dry soil is weighed in duplicate into 50-cc. nickel crucibles.   To each crucible is added 10 cc. of a solution containing 4 gm. KOH, and the mixture is placed on a sand bath until dry.   The crucibles are then ignited over a Meker burner, cooled, and 7.5 cc. of distilled water is added to

each. After standing 1 hour or longer, the contents are triturated thoroughly with a rubber policeman and transferred to a 50-cc. centrifuge tube calibrated at 35 cc. and placed in a 300-cc. Erlenmeyer flask of cold water. The crucibles

TABLE 3

Total and water-soluble boron and their ratios in some surface soils from Illinois and Georgia

SOIL TYPE	FIELD	PRODUC-TIVITY RATING (ALEDO = 100)	BORON		
			Total	Water-soluble	Ratio Total/ Water-soluble
			p.p.m.	*p.p.m.*	
Grundy silt loam..........	Aledo, Ill.	100	44	0.75	59
			35	0.85	41
			30	0.50	60
Muscatine silt loam........	Dixon, Ill.	79	27	0.52	52
			32	0.65	49
			36	0.69	52
Grundy silt loam..........	Carlinville, Ill.	56	21	1.22	17
			20	1.19	17
Cisne silt loam............	Oblong, Ill.	29	47	0.45	104
			33	0.33	100
			n.d.*	0.43	..
			n.d.	0.24	..
			n.d.	0.20	..
Cisne silt loam............	Toledo, Ill.	25	18	0.43	42
			27	0.38	71
Yellow-gray silt loam......	Raleigh, Ill.	20	31	0.22	141
			n.d.	0.28	..
Clement silt loam.........	Elizabethtown, Ill.	15	45	0.40	112
			39	0.48	81
Cecil sandy clay loam......	Experiment, Ga.		52	n.d.	..
Davidson clay loam........	Woodbury, Ga.		52	n.d.	..
Norfolk loamy sand........	Hazelhurst, Ga.		5	n.d.	..
Norfolk sandy loam........	Hazelhurst, Ga.		10	n.d.	..
Ruston sandy loam........	Ellaville, Ga.		45	n.d.	..

* n.d. = not determined.

are rinsed with two successive 5-cc. portions of $(1 + 3)$ H_2SO_4 which are added to the contents of the tube. After the effervescence has diminished, 10 cc. of concentrated H_2SO_4 is added, and the tubes are stoppered and thoroughly shaken. In 5 minutes, 5 cc. of $(1 + 3)$ H_2SO_4 containing 0.5 gm. $Fe(NH_4)_2(SO_4)_4$

·6H$_2$O is added to the tube and the mixture is made to volume with 10 N H$_2$SO$_4$. After shaking again, the tube and contents are allowed to stand 1 hour and then are centrifuged for 5 minutes at 2000 r.p.m. If desired, the soil-sulfuric acid mixture may be filtered. The apparatus shown in figure 1 was found convenient for this filtration. Whatman No. 42 filter paper was used.

Before routine soil determinations were made, this method was checked against the alcohol-distillation procedure and with soils to which boron had been added. On soils of high, medium, and low boron content, the results obtained by the sulfuric-acid extraction compared favorably with those obtained by distillation. Results shown in table 2 indicate that in only one of four soils was a complete recovery of added boron obtained, yet the recoveries are considered satisfactory in view of the difficulty of the determination. In a reproducibility study, successive individual determinations on Norfolk sandy loam varied from 8 to 11 p.p.m. of boron and on Clement silt loam from 43 to 52 p.p.m. When averages of duplicate or triplicate determinations were used, successive determinations were in good agreement.

Determinations for total boron were made, by the method described, on surface soil samples from experimental plots in Illinois and Georgia. The data obtained are presented in table 3.

WATER-SOLUBLE BORON

Before the quinalizarin method was adapted for use with the photoelectric colorimeter, determinations were made by visual colorimetry for boron in Illinois and Georgia soils extracted with boiling water. Although the water-soluble fraction is not an exact index of the boron in the soil available to the plant, yet this portion is probably a truer measure of the available form than either the acid-soluble fraction or the total. The method used, a modification of that proposed by Berger and Truog (3), is as follows:

Forty grams of air-dry, 20-mesh soil is placed in a 250-cc. Erlenmeyer flask of Kavalier glass, and 80 cc. of distilled water is added. The flask containing the mixture is attached to a reflux condenser and the contents are boiled for 5 minutes. The Erlenmeyer is removed and stoppered and the contents are allowed to cool. The mixture is filtered with suction through a dry paper on a Büchner funnel and 60 cc. of the filtrate is evaporated to dryness in a nickel crucible after the addition of three drops of 40 per cent K$_2$CO$_3$ solution. (Potassium carbonate is added until the liquid is basic to litmus paper.) The residue is gently ignited, 5 cc. of 0.36 N H$_2$SO$_4$ added, and the mixture thoroughly triturated with a policeman, transferred to a 16- x 50-mm. shell vial calibrated at 6 cc., and made to volume with 0.36 N H$_2$SO$_4$. The solution is filtered into a 70- x 15-mm. funnel tube and 1 cc. of the filtrate is pipetted into a 15- x 90-mm. shell vial. Nine cubic centimeters of 98.5 per cent by weight H$_2$SO$_4$ is run into the vial from a burette. The tube is then stoppered and the contents are allowed to cool. To the cool solution in the tube is added 0.5 cc. of 0.01 per cent quinalizarin solution. The mixture is stirred thoroughly and

is compared after one-half hour or longer with standards prepared in the same way. The results of these determinations are given in tables 3 and 4.

The water-soluble boron in Georgia soils studied ranged from 0.01 to 0.65 p.p.m., and in the Illinois soils from 0.20 to 1.22. No general relationship was found between the water-soluble boron and fertilizer treatment. As a group, the soils from Georgia are much lower in water-soluble boron than the Illinois soils. The small amount in the Coastal Plain soils of Georgia (Norfolk and

TABLE 4

Water-soluble boron in soils of some Georgia experimental plats

SOIL TYPE	FIELD	FIELD PRODUC-TIVITY (CEDAR-TOWN = 100)	TREATMENT PER ACRE			WATER-SOLUBLE BORON IN DRY SOIL	
			N	P₂O₅	K₂O	Plat	Average
			pounds	*pounds*	*pounds*	*p.p.m.*	*p.p.m.*
Decatur clay loam	Cedartown	100	0	0	0	.65	
			32	32	32	.46	.55
Carnegie sandy loam	Carnegie	81	0	0	0	.19	.19
Cecil sandy clay loam	Experiment	73	0	0	0	.08	
			0	54	36	.10	
			36	36	36	.11	
			36	36	36*	.13	.11
Norfolk sandy loam	Waynesboro	64	0	0	0	.01	.01
Cecil sandy loam	Yatesville	44	0	0	0	.08	.08
Norfolk sandy loam	Hawkinsville	36	36	36	36	.04	
			36	36	36†	.08‡	
			36	36	36§	.06	
			36	36	36†§	.24‡	.05

* And 1000 pounds limestone.
† And 5 pounds borax.
‡ Not included in average.
§ And limed to pH 6.0.

Carnegie) may be one of the factors responsible for the harmful effects which sometimes occur when these soils are limed. The limed plats studied, however, contained as much water-soluble boron as those which were not limed (9). On some of the Oblong plats (Illinois), on the Toledo field, and at other locations in southern Illinois, symptoms resembling those of boron deficiency have been noted on lespedeza, alsike, and red clover. There is not sufficient difference in the water-soluble boron in the various plats to verify these observations, although it is less than 0.5 p.p.m. as compared to values of 0.5 p.p.m. or greater in the soils where no symptoms appeared.

As may be noted from table 3, the total boron does not bear a definite relationship to the water-soluble fraction. This observation is similar to findings reported by Robinson, Whetstone, and Byers (11). Some of the boron in the soils studied is present as the inactive mineral tourmaline. The total boron in the Illinois soils ranged from 18 to 47 p.p.m. and in the Georgia soils from 5 to 52.

The data in table 3, except those from Carlinville, point to a parallelism between the water-soluble boron in the soil and productivity. This may or may not represent a causal relationship. Soils high in productivity contain more water-soluble boron than soils of lower productivity. Indications from the data for Georgia soils (table 4) are less conclusive, but Decatur clay loam, the most productive soil, is highest in water-soluble boron. Though this investigation has not resulted in positive conclusions, it is the authors' judgment that its continuation in both states is justified, particularly with regard to the relative availability of different forms of boron and their sufficiency or deficiency for crop production in the different soil groups.

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THE SURVIVAL OF MICROORGANISMS IN ALKALI SOILS

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In many soils on which the annual rainfall is less than 20 inches, soluble salts accumulate to such an extent that the soils are barren or support only scant vegetation composed of salt-resistant plants. In addition to their osmotic and toxic effects upon plants, salts also injure vegetation through their effects upon the soil microflora. Nitrification, ammonification, and nitrogen fixation may be accelerated or retarded depending upon the kind and concentration of salt present. The concentration at which soluble salts completely inhibit or destroy the various soil microorganisms is unknown. It is the purpose of this paper to consider the effects of high concentrations of soluble salts acting over long periods upon the microflora of the soil.

PLAN OF THE EXPERIMENT

The work was conducted on four different soils: Corinne soil which contained 1.8 per cent total soluble salt, 38.9 per cent of which was chlorides, 59.3 per cent sulfates, and 1.8 per cent carbonates; Richland acre soil which contained 1.8 per cent total soluble salts, 0.3 per cent of which was chlorides, 89.4 per cent sulfates, and 10.3 per cent carbonates; Benson soil which contained 1.7 per cent total soluble salts, 25.9 per cent of which was chlorides, 60.9 per cent sulfates, and 13.2 per cent carbonates; and College farm soil rendered barren by the addition of 2 per cent sodium chloride, 2 per cent sodium sulfate, 2 per cent sodium carbonate, 1 per cent each sodium chloride and sodium sulfate, 1 per cent each sodium chloride and sodium carbonate, 1 per cent each sodium sulfate and sodium carbonate, and $\frac{2}{3}$ per cent each sodium chloride, sodium sulfate, and sodium carbonate.

The soils were packed into 2-gallon jars having a half-inch hole near the bottom. They were allowed to stand for 2 months with a 20 per cent moisture content, after which one-half of them were kept covered with water for 640 days. At the end of this time, both the leached and the unleached soils were planted to crimson clover. During the next 3 years they were watered occasionally, and the crop was harvested from the productive soils. At the end of the 5 years the soils were air dried and were stored in mason fruit jars for 20 years. The following determinations were then made: total number of microorganisms developing in synthetic glucose agar, and the ammonifying, nitrite-producing, nitrate-producing, and nitrogen-fixing powers.

Number of microorganisms. The number of microorganisms in the soil was determined by plating on Lipman and Brown's (7) synthetic glucose agar to which had been added 0.004 per cent ammonium sulfate. Each sample of soil was thoroughly mixed, 10 gm. weighed into 200 cc. sterile tap water, and dilutions made so that plates could be poured with dilutions of 1 to 20,000 and 1 to 200,000. The plates were incubated for 4 days and then counted.

Ammonification. The ammonifying powers of the soil were determined by seeding 1 gm. of the thoroughly mixed soil into 100 cc. of a 1 per cent sterile peptone solution and then incubating for 7 days at 28°C. The ammonia was determined by transferring to Kjeldahl flasks, adding 2 gm. of magnesium oxide, and distilling into 0.1 N H_2SO_4.

Nitrite production. The nitrites produced by the soils were determined by seeding 1 gm. of thoroughly mixed soil into 100 cc. of Winogradsky's medium (7), and incubating at 28°C. for 21 days. The nitrite nitrogen was determined by the sulfanilic acid method.

Nitrate production. The nitrates produced were determined by seeding and incubating as for nitrites. The nitric nitrogen was determined by the phenoldisulfonic acid method.

Nitrogen fixation. The nitrogen-fixing powers of the soil were determined by seeding 1 gm. of thoroughly mixed soil into 100 cc. of Greaves' medium (6). The method was as follows: The medium was distributed in 100-cc. portions into 500-cc. Erlenmeyer flasks, to each of which was added 0.5 gm. of calcium carbonate. The flasks were autoclaved at 120°C. for 15 minutes. Each flask was then inoculated with 1 gm. of the soil and incubated at 28°C. alongside sterile checks for 21 days. The total nitrogen was determined by the Gunning-Hibbard method.

EXPERIMENTAL RESULTS

The average results obtained from five replicate closely agreeing determinations of the number of microorganisms developing upon glucose agar and of each of the processes evidencing survival or nonsurvival of the different types of organisms in the soil are given in table 1.

It has been shown elsewhere (4) that all the synthetic alkali soils except those to which sodium carbonate was added produced crimson clover. The quantity produced varied with the specific soil. The leaching of the soils increased their productivity. This was true even in the case of the fertile college farm soil. The results pointed to the conclusion that the increased productivity observed in the leached soil is due to an increased bacterial activity which rendered available more plant food.

The leaching of the soil materially increased the numbers of microorganisms which developed on synthetic glucose agar (table 1). In the unleached soils to which sodium carbonate was added and in the unleached Benson alkali soil, the numbers were very low. Molds predominated, yet a rich varied bacterial flora developed on the glucose agar, as was shown by an examination of the

different colonies.   Many of these were nonsporeformers, indicating that even vegetative bacteria can withstand the high osmotic pressure of these salts over long periods.

It is evident from the ammonia determinations (table 1) that the ammonia-producing microorganisms survive for at least 20 years in soils having high concentrations of alkali salts.   In these soils, held in air-dried condition for 20 years, it is probable that the water film surrounding each particle and in which many of the microorganisms occurred would be saturated with a soluble salt. It is even probable that metabolism and multiplication of the microorganisms occur in the soils, for it was found that when sterile dried blood was added to

TABLE 1

Number of microorganisms developed on glucose agar, ammonia and nitrous and nitric nitrogen produced, and nitrogen fixed by soils air-dried for 20 years*

SOIL	NUMBER OF MICRO-ORGANISMS		AMMONIA		NITRATE NITROGEN		NITRITE NITRO-GEN	NITROGEN FIXED	
	Leached	Unleached	Leached	Unleached	Leached	Unleached		Leached	Unleached
	thou-sands	thou-sands	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
College farm soil	3,300	2,100	98	86	6	5	1	6.0	5.3
College farm soil — 2% NaCl	688	181	103	103	7	0	0	5.2	6.3
2% Na₂SO₄	2,310	298	98	98	10	0	0	6.0	5.6
2% Na₂CO₃	732	66	100	90	9	0	0	5.2	3.8
1% each NaCl, Na₂SO₄	555	470	96	104	6	0	0	7.1	4.7
1% each NaCl, Na₂CO₃	1,130	510	96	107	11	0	0	6.1	6.8
1% each Na₂CO₃, Na₂SO₄	995	312	95	99	12	0	0	...	...
⅓% each NaCl, Na₂SO₄, Na₂CO₃	849	212	99	84	6	0	0	5.9	6.4
Corinne alkali soil	730	293	89	90	4	0	0	4.8	5.4
Richland acre alkali soil	530	279	89	85	9	0	0	4.4	4.8
Benson alkali soil	3,045	30	90	72	4	0	0	4.6	1.6

* See text for detailed description of determinations.

the soils nitrogen was rapidly split off as ammonia.   It is probable that the action of ammonifiers has not been stimulated by the alkali salts but that the larger quantities of ammonia accumulating are the result of the absence of nitrifiers.

It has been shown elsewhere (2) that if we use as a measure of activity of alkali salts that quantity of salt which if applied to a definite weight of soil either increases or decreases the quantity of ammonia produced in the soil as compared with a similar untreated soil kept under similar conditions, we find that most soluble salts first stimulate and then retard ammonification.   The extent to which this occurs depends upon both anions and cations.   Comparatively small quantities of the salts retard ammonification, but large quantities are needed to reduce to two-thirds the quantity of ammonia produced.

Greaves and Lund (1) have shown that some salts slightly retarded ammonification when the osmotic pressure ranged from 1.65 to 1.95 atmospheres, but the microorganisms were still functioning in soil having an osmotic pressure of 45 atmospheres. From the data herein reported, it is evident that soluble salts may accumulate in a soil in quantities sufficient to retard ammonification but it is not likely that they would ever accumulate in sufficient quantities to destroy the ammonifying microorganisms.

Greaves (2) has shown that alkali salts become toxic to nitrifying bacteria at a much lower concentration than they do to the ammonifying microorganisms. Greaves and Lund (1) showed that an osmotic pressure of 1 to 2 atmospheres materially retarded the activities of nitrifiers and at 8 atmospheres nitrate production ceased.

As shown in table 1, neither nitrites nor nitrates were produced when the alkali soils of the present experiment were inoculated into appropriate media. Qualitative tests were made on numerous samples incubated for different periods, and the results were always negative with the alkali soil but positive with the untreated college farm soil.

In the results of the determinations of nitrogen fixed when these soils were seeded into an appropriate medium (table 1), there is evidence that the nitrogen-fixing power of some of the soils is increased by some alkali salts. This is especially the case where two salts are used in combination. The antagonistic action of one salt to the toxicity of another, as was first observed in bacteria by Lipman (8), is brought out in this work. In general, the fixation in the medium seeded with the nonleached alkali soil is only slightly less than that in the medium seeded with the leached soil, thus showing that the nitrogen-fixing microflora of these soils not only withstand for long periods high concentrations of soluble salts but they can actually grow in the presence of appreciable quantities of soluble salts.

Characteristic Azotobacter films formed on synthetic media inoculated with leached and nonleached synthetic alkali soil and Richland acre soil. In fact, the membrane formed earlier and was darker in the presence of sodium sulfate than in its absence. Furthermore Azotobacter has been recovered from solutions producing typical membranes but no Azotobacter has been obtained from either the Benson or the Corinne alkali soil. It is evident from the results, however, that the last two soils carry nitrogen-fixing microorganisms. One of us (5) isolated from these soils 11 microorganisms which, when cultured in soil with an optimum moisture content and appropriate carbohydrate, fix nitrogen. The quantity of nitrogen fixed varied with the specific microorganism and the carbohydrate added to the soil. Some of the microorganisms fixed as much as 1.4 mgm. of nitrogen in 10 gm. of soil. Furthermore, it was demonstrated that the nitrogen fixed did not come from pyrrole compounds in the soil or from combined atmospheric nitrogen (3).

It has been demonstrated that the chlorides, sulfates, and carbonates of sodium increase nitrogen fixation when added to a highly productive calcareous

soil and that these compounds do not become toxic when added in quantities equivalent to 460 p. p. m. of sodium. Now the data in table 1 has demonstrated that nitrogen-fixing microorganisms will survive for at least 20 years in soils containing 2 per cent of alkali salt.

DISCUSSION

Barren alkali soils contain a rich microflora, as do also artificially produced alkali soils containing 2 per cent of sodium chloride, sodium sulfate, or sodium carbonate, either individually or in combination. In such soils held under air-dry conditions the microorganisms have survived for 20 years.

Small quantities of alkali salts increase the accumulation of ammonia in the soil. This may be due to an actual increase in the rate of ammonia production or to a retardation in the production of nitrates. It has been shown elsewhere (2) that soils containing large concentrations of "alkali salts" ammonify proteinaceous materials when these are added to the soil and the soil is held under optimum temperature and moisture conditions. However, the alkali salts retard the process. This retardation is greatest in the case of sodium carbonate and least in the case of sodium sulfate. The ammonifying microorganisms survived for 20 years in the presence of high concentrations of soluble salts. They undoubtedly withstand great osmotic pressure, for if it is assumed that most of the salts are in solution, the water would be saturated when the soil is air-dried, and when the soil is saturated with water the concentration of the various salts in the soil water would be approximately 10 per cent. It is even probable that these microorganisms metabolized in such a medium, for when sterile dried blood was added to the soil, ammonia was liberated.

The nitrite- and the nitrate-producing bacteria are far more sensitive than the ammonia-producing organisms. Small quantities of alkali salts stimulate nitrifiers but as the concentration increases, their activities are retarded. No Nitrosomonas or Nitrobacter organisms survived the treatment for 20 years, nor were they found in the naturally occurring barren alkali soils until these had been treated with various plant residues or extracts from fertile soils.

Azotobacter, together with other nitrogen-fixing microorganisms, resists over long periods high concentrations of soluble salts, and even fixes appreciable quantities of nitrogen in soil highly impregnated with alkali salts. This work demonstrates that the sensitivity of various soil microorganisms to salts varies widely. It is greatest in the case of the nitrifiers and least in the case of the nitrogen fixers.

It is important to note that alkali salts become toxic to nitrifying microorganisms before they become toxic to many higher plants. It is probable, therefore, that the injuries first observed when land starts to "go bad," as the result of an accumulation of "alkali," are due to the action of the salts upon the nitrifiers, and only when these salts become more concentrated do they directly injure the plant. Moreover, after a soil has been leached of its "alkali" it is a

number of years before it is productive. This unproductive period is due, in a measure, to the poor physical condition of the soil; however, this is not the only factor, for the addition of manure or extracts of productive soil greatly shortens the unproductive period.

SUMMARY

Alkali soils containing approximately 2 per cent of soluble salts were kept for 20 years under air-dry conditions. At the end of this time the following determinations were made: total number of microorganisms developing on a synthetic glucose agar, and the ammonifying, nitrite-, and nitrate-producing organisms, and nitrogen-fixing powers. From 30,000 to 2,000,000 microorganisms, depending upon the specific salt present, developed. All soils had an active ammonifying microflora which compared favorably with that of fertile soils. Nitrosomonas and the Nitrobacter were apparently absent from the soil, for neither nitrites nor nitrates were produced when the soils were inoculated into appropriate media. *Azotobacter chroococcum* was found in some of the soils even after 20 years. These actively fixed nitrogen when seeded into an appropriate medium.

Hence ammonifying and nitrogen-fixing microorganisms can survive for long periods in soil, the water of which is saturated with sodium chloride, sodium sulfate, or sodium carbonate, either individually or in combination. The nitrite- and nitrate-producing bacteria, however, disappear from such soils.

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SOURCES AND DISTRIBUTION OF IODINE IN SOUTH CAROLINA WITH SPECIAL REFERENCE TO TYPES OF SOIL AND ROCKS[1]

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Iodine is widely distributed in nature. It has been found in rocks, soils, deep well waters, rivers, coal, and the air. Reports by various workers from many sections of the country indicate that it is more abundant in certain areas than in others.

The soils and plants along the Atlantic seaboard are thought to contain more iodine than those in other sections of the country. This is partly because the area was once covered by the sea, which left, as it receded, deposits of salts, fish residues, and organic matter, all of which contain some iodine. There is also the remote possibility that sea vapors have carried small quantities of dissolved salts containing iodine and distributed this material a long way inland.

The soils along the coast may contain considerable iodine, but many investigators have shown that iodine is also found far inland in rather large amounts.

According to McHargue, Young, and Calfee (8), the iodine content of soils from six principal geological areas in Kentucky varied from 0.81 to 19.95 p.p.m. McHargue, Roy, and Pelphrey (7) also have found that Kentucky limestone contains 0.8 p.p.m. of iodine and Kentucky phosphate rock and Tennessee phosphate rock 6.7 and 5.5 p.p.m. respectively. The locale of these studies is more than 500 miles from the present shore line, but was covered by the ocean at one time.

Remington, Culp, and Von Kolnitz (11), in comparing the iodine content of Irish potatoes grown in various sections of South Carolina, found the greatest amount in those grown in the Piedmont section, or the upper part of the state.

A survey of the iodine content of soils in New Zealand made by Hercus, Benson, and Carter (6) revealed from 0.2 to 20.0 p.p.m., depending upon the location. Von Fellenberg (3) found the iodine content of soils in Switzerland to be from 0.62 to 11.9 p.p.m.

DISTRIBUTION OF IODINE IN SOUTH CAROLINA

The iodine content of vegetables grown in South Carolina is very high, especially in comparison with results reported from other sections of the United States. Remington and Weston (12) in their work on vegetables in South Carolina have shown much larger quantities of iodine than those found in California and Oregon. Mitchell (9, 10), reporting on iodine in vegetables, feeds, and river waters in South Carolina, shows rather large quantities. The results indicate that the element is widely distributed, with possibly more in the Piedmont area than in the Coastal Plains.

To obtain more evidence and information on the source of the iodine, a study was made of many of the typical soils in the state and also of some of the parent rocks.

GEOLOGY OF THE STATE

Some of the older rocks of the state are gneiss, some granites, schists, and slates. The following may be listed as some of the principal parent materials from which soils have been derived:

> Acid crystalline rocks (granite, gneiss)
> Basic crystalline rocks (diorite, hornblende, schist)
> Micaceous schists (high mica "isinglass rock," mica schists, mica predominating)
> Slates (acid slates and basic slates)
> Sandstones and shales

South Carolina may be divided into two main regions, the Uplands and the Coastal Plains, composing approximately one-third and two-thirds, respectively, of the area of the state (2). These regions may be further divided into eight provinces: 1, Mountain; 2, 3, and 4, Upper, Middle, and Lower Piedmont; 5, Sandhills; 6, 7, and 8, Upper, Middle, and Lower Coastal Plains. These areas are shown in figure 1.

The Uplands may or may not have been covered by the ocean at one time, but there is conclusive evidence that the Coastal Plains region was under water. The evidence indicates that the shore line extended from a point near Augusta, Georgia, on the western boundary through Columbia in the center of the state to Chesterfield County on the eastern boundary. From this line the shore gradually receded in successive stages to the present location.

Since at some remote period, one-half the state was out of water and the other half submerged, it might be well to consider what effect this general condition had on the formation of soils in these two areas. The Uplands soils were formed principally from the disintegration of the adjacent rocks and the accumulation of organic matter from vegetation. The Coastal Plains soils, on the other hand, may be considered as a cosmopolitan mixture made up from many soils of the Upland area. The heavy rains of the Piedmont region washed the lighter material from this area into the streams, which

carried it on to the ocean where it was systematically distributed according to weight and size of particles.
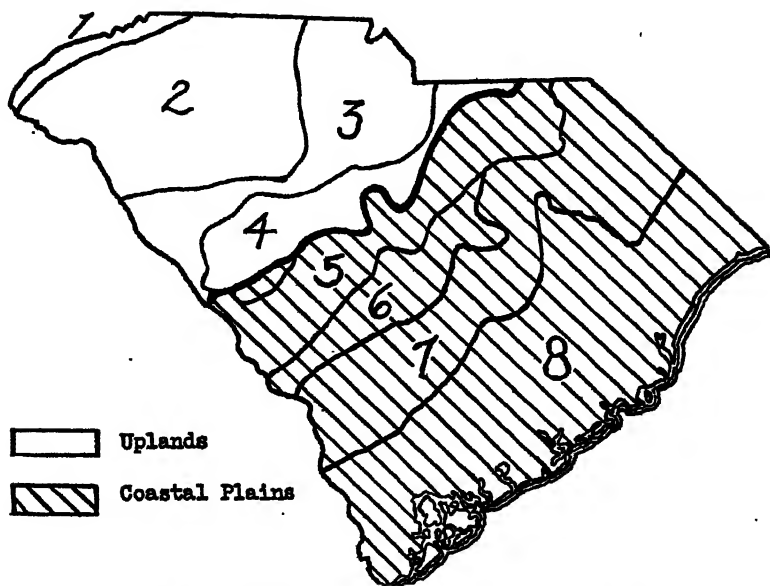
FIG. 1. MAP OF SOUTH CAROLINA, SHOWING LOCATION OF PROVINCES

1, Mountain; 2, 3, 4, Upper, Middle, and Lower Piedmont; 5, Sandhills; 6, 7, 8, Upper, Middle, and Lower Coastal Plains. The heavy line between 4 and 5 indicates the original coast line.

COMPOSITION OF ROCKS IN THE PIEDMONT

Table 1 shows the amount of iodine in some of the common parent rocks in the upper Piedmont region.

TABLE 1

Iodine in parent rocks from Upper Piedmont region

PARENT ROCK	SOURCE	IODINE CONTENT
		p.p.m.
Gneiss	Pickens Co., S. C.	3.88
Gneiss	Pickens Co., S. C.	4.17
Gneiss	Highlands, N. C.	3.34
Gneiss	Lake Toxaway, N. C.	1.32
Gneiss (weathered)	Oconee Co., S. C.	2.35
Mica schists	Pickens Co., S. C.	16.54
Schist	Pickens Co., S. C.	11.11
Mica schists	Pickens Co., S. C.	2.00
Mica schists	Oconee Co., S. C.	2.73
Quartz and mica	Oconee Co., S. C.	1.85
Feldspar	Clingsman's Dome, N. C.	2.18

TABLE 2

Iodine content of some soils of South Carolina

SOIL SERIES AND HORIZON	ORIGIN	IODINE CONTENT
		p.p.m.
Mountain soils		
Ashe A_1		6.03
Ashe B_1		8.20
Porters A_1	Derived from gneisses and	9.52
Porters B_1	other granitic rocks	8.13
Hayesville A_1		9.35
Hayesville B_1		8.55
Piedmont residual soils		
	Upper Piedmont Section	
Durham A_1		10.40
Durham B_1		7.94
Cecil A_1	Derived from granites, gneiss, and schist	11.63
Cecil B_1		11.90
Louise A_1		9.26
Louise B_1		14.49
Appling A_1	Derived from mica schist and quartz mica schist	7.44
Appling B_1		9.09
Appling C_1		9.57
Surry A_1		6.25
Surry B_1		8.06
Worsham A_1		3.21
Worsham A_2		3.39
Worsham B_1	Derived from mixed basic and acid rocks	6.99
Helena A_1		9.09
Helena B_1		9.17
	Middle Piedmont Section	
Mecklenburg A_1		10.91
Mecklenburg B_1		14.29
Mecklenburg C_1		7.14
Iredell A_1	Derived from basic diorites and hornblende schist	8.62
Iredell B_1		8.13
Iredell C_1		7.14
Davidson A_1		13.51
Davidson B_1		11.90

TABLE 2—*Continued*

SOIL SERIES AND HORIZON	ORIGIN	IODINE CONTENT
		p.p.m.
Piedmont residual soils—Concluded		
	Lower Piedmont Section	
Alamance A₁		4.95
Alamance B₁		6.06
	Derived from slates, shales, and igneous rocks (acid)	
Georgeville A₁		8.93
Georgeville B₁		7.69
Georgeville C₁		6.15
Orange A₁		3.85
Orange B₁		4.17
	Derived from slates, shales, and igneous rocks (basic)	
Tirzah A₁		4.90
Tirzah B₁		40.00
Wickham A₁	Derived from Piedmont and Mountain material (Second bottom)	11.36
Wickham B₁		9.26
Sandhills soils		
Norfolk A₁		3.12
Norfolk B₁		3.75
Grady A₁		2.14
Grady B₁		2.19
Roanoke A₁		2.13
Roanoke B₁		3.09
Upper Coastal Plains soils		
Orangeburg A₁		1.83
Orangeburg B₁		2.17
Orangeburg C₁		6.41
Marlboro A₁		5.17
Marlboro B₁		9.26
Tifton A₁		6.02
Tifton B₁		9.62
Blakely A₁		6.06
Blakely B₁		7.78
Chesterfield A₁		2.38
Chesterfield B₁		4.43
Greenville A₁		4.27
Greenville B₁		5.43

TABLE 2—*Concluded*

SOIL SERIES AND HORIZON	ORIGIN	IODINE CONTENT
		p.p.m.
Middle Coastal Plains soils		
Coxville A$_1$		5.16
Coxville B$_1$		4.63
Cowdle A$_1$		4.17
Cowdle B$_1$		4.55
Kalmia A$_1$		4.03
Kalmia A$_2$		3.38
Kalmia B$_1$		3.85
Lower Coastal Plains soils		
Hyde A$_1$		5.68
Hyde B$_1$		2.35
Bayboro A$_1$		1.50
Bayboro B$_1$		1.65
Bayboro C$_1$		2.14

Gautier (5) determined the iodine content of a number of rocks to be the following: granite, 1.25 p.p.m.; mica, 0.78 p.p.m.; and apatite, 0.23 p.p.m. Von Fellenberg and Lunde (4) compared the iodine content of soils with that of rocks from which the soils were derived and found the following:

PARENT ROCK	IODINE CONTENT OF ROCK	IODINE CONTENT OF SOIL.
	p.p.m.	*p.p.m.*
Gneiss	0.38	1.32
Amphibolite	0.38	3.15
Red dolomite	1.00	2.00

EXPERIMENTAL

The soils used in this investigation were obtained from the department of agronomy of the South Carolina Experiment Station.[2] They were selected according to horizons and should be fairly representative of the topsoil, subsurface, and parent material.

The chemical analysis of the soils and rocks was made according to the fusion method, Official Methods of Analysis (1, pp. 6–7), with some slight variations. The results are recorded in table 2 according to soil provinces and to some extent according to parent sources.

[2] The author wishes to thank W. R. Paden and H. T. Polk for their cooperation.

Some large differences in iodine results are noted, which may be partly due to the manner in which the soils were formed. The parent material of the soils in the Piedmont region contains considerable iodine, and in the process of soil formation the possibility of loss of iodine was not so great as in the transported soils. A large part of the soil which makes up the Coastal Plains was transported from the Uplands and much of the iodine may have been lost through oxidation. It is also possible that the Uplands soils have greater retentive power for iodine salts, resulting in less rapid leaching than occurs in the more sandy soils.

The average iodine content of the soils of the Uplands is 8.98 p.p.m., and that of the Coastal Plains is 3.77 p.p.m. There is not a great variation in the iodine content of the 14 individual soils from the Coastal Plains. Of the Coastal Plains Provinces, the Sandhill soils have the average content, 2.74 p.p.m.; and the Upper Coastal Plains, 5.45 p.p.m.; the Middle Coastal Plains have 4.25 p.p.m. and the Lower Coastal Plains 2.66 p.p.m.

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THE IMPORTANCE OF SODIUM FOR PLANT NUTRITION: II. EFFECT ON BEETS OF THE SECONDARY IONS IN NITRATE FERTILIZERS

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Having established, in the first paper of this series (4), the importance of sodium to the plant, we will now consider a particular form of sodium fertilization, in which the anion determines the main effect, but in which the effect of the cation cannot be disregarded.

The preceding paper referred to the investigations by Wagner, who emphasized the effect of the secondary ion in nitrogen fertilizers. Schulze (6) also pointed out later that the effect of nitrate of soda is based not only on the form of its nitrogen, but also on its sodium content. Maschhaupt (5) presented data from a field experiment on sandy clay conducted by the State Agricultural Station of Groningen over a long period (1911–1934), showing that nitrate of soda produced yields of fodder beet, flax, potato, canary seed, and peas that were, in general, superior to those obtained with $(NH_4)_2SO_4$, NH_4NO_3, or $Ca(NO_3)_2$. Because of the differences established between $NaNO_3$ and $Ca(NO_3)_2$, Maschhaupt is inclined to ascribe the favorable results often obtained with $NaNO_3$ not only to its nitrate form, but also to its sodium content. He attributes the increasing deficiency of potassium in the sandy clay soils of the Province of Groningen not only to decreased use of farmyard manure and the growth of crops with high potassium demands, but also to the ever-declining use of nitrate of soda as a nitrogenous fertilizer. He points out that the sodium accumulated in the soil during the course of years by the application of nitrate of soda, an accumulation that might help to supply the plant's need for bases, will gradually be exhausted.

What factors determine the nature and intensity of the secondary effects of the cations in nitrate fertilizers? Experiments on permeability and on assimilation by many workers have demonstrated that, for normal development of the plant, cations must be present in a certain ratio. The yield also depends on this ratio. It is chiefly, Na, K, Ca, and Mg which determine the situation.

The same experiments showed that the form in which the cations are present is of considerable importance and that the anion can exercise strong influence on the assimilation of the cations. Potassium, for instance, is assimilated from a solution of KNO_3 more readily than from KCl, and from KCl more readily than from K_2SO_4. Even when the assimilation of cations is assumed

to be effected chiefly by contact absorption, as suggested by Jenny and Overstreet (3), the influence of the anion must also be manifest in weakly buffered systems. Consequently, nitrate fertilizers may be expected to have a more pronounced effect of secondary ions than, for instance, chloride or sulfate dressings.

On the premise that the mutual ratio of the cations influences both the state of health and the production of the plants, fertilizing obviously plays an important part because of its potentialities for causing changes in this system. Nevertheless, agricultural practice seldom takes this into account, because the dominant role of regulation is assigned to the adsorptive complex. As explained in a previous article (1), this is a mistake in many instances, the buffering effect of the soil being overestimated.

The following results, obtained with pot cultures, show the differences in effect of $NaNO_3$, $Ca(NO_3)_2$, and NH_4NO_3.

EXPERIMENTAL

Experiments were begun in 1937 (1, 2) to test the effect of several forms of nitrate fertilizers[1] on the Barres variety of fodder beet grown in pots of sandy soil having a pH of 6.5 and containing 3.4 per cent humus and 4.3 per cent clay.

Experiment 1

During the first year, in which increasing nitrogen applications were compared, it was observed that growth of the plants treated with calcium nitrate remained distinctly inferior to that of plants treated with sodium nitrate. The enormous differences in yields are shown graphically in figure 1.

Experiment 2

In 1938, sodium nitrate and calcium nitrate were again compared, this time in conjunction with increasing levels of potassium. The experiment was run in Brenchley pots containing 6 kgm. of soil and a basic treatment of 2.15 gm. $CaHPO_4 \cdot 2H_2O$, 1.2 gm. $MgSO_4 \cdot 7H_2O$, and a few drops of a 5 per cent solution of $FeCl_3$. Moisture was maintained at 60 per cent of the water-holding capacity. The pots were in triplicate. The quantity of nitrogen applied was 2400 mgm. per pot, one half as a basic fertilizer and the other half as a top-dressing. Potassium, as KCl, was added as follows, three fifths as a basic application and two fifths in the form of a top-dressing: (a) 525 mgm. K—low K; (b) 900 mgm. K—normal K; (c) 1275 mgm. K—high K; and (d) 1650 mgm. K— very high K.

At a very early stage of plant growth, distinct differences could be noted between the $NaNO_3$ and the $Ca(NO_3)_2$ series. The latter showed increasing retardation during the course of growth, only the group receiving the very

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[1] The original purpose of these experiments was to establish differences in boron effect of various treatments. All the treatments compared in this paper, however, include equivalent quantities of boron, whose influence on yield differences between treatments is thus eliminated. Boron is, therefore, disregarded in this discussion.

high K addition being a more or less favorable exception. Apart from their backward state, all the plants of the Ca(NO₃)₂ series were readily distinguishable in color and growth habit from those of the NaNO₃ series. The foliage of the latter was, in general, abundant, spreading, and light green in color.
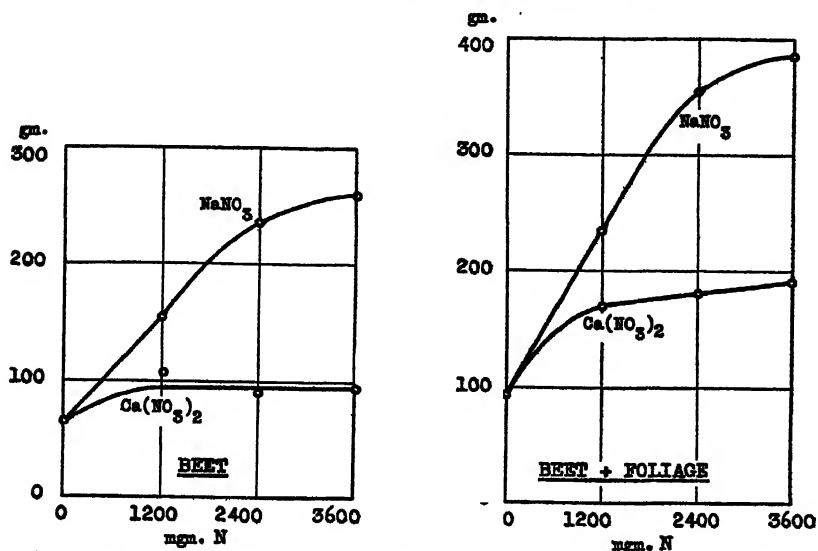
FIG. 1. COMPARISON OF THE YIELDS OF BEETS FERTILIZED WITH CALCIUM NITRATE AND WITH SODIUM NITRATE

Dry matter for three pots—experiment 1

TABLE 1

Average yields of dry matter, in grams per pot, of beet plants grown with NaNO₃ and with Ca(NO₃)₂, to which were added increasing quantities of potassium

K APPLICATIONS .....*mgm.*	525	900	1275	1650
Beet:				
NaNO₃...........	54.9 ±0.4	57.4 ±7.4	65.4 ±4.8	67.5 ±6.2
Ca(NO₃)₂.........	32.9 ±2.8	31.2 ±2.7	38.1 ±7.1	45.3 ±6.3
Foliage:				
NaNO₃...........	39.2 ±0.8	41.9 ±0.4	35.7 ±2.4	46.9 ±1.8
Ca(NO₃)₂.........	39.6 ±2.9	41.1 ±0.1	38.4 ±2.2	42.3 ±1.1
Total:				
NaNO₃...........	93.4 ±0.6	99.3 ±7.3	101.1 ±3.7	114.3 ±7.6
Ca(NO₃)₂.........	72.6 ±0.1	72.4 ±3.3	76.5 ±8.0	87.6 ±6.5

The growth habit of the plants receiving calcium nitrate, on the other hand, was compressed, with leaves of a dark, somewhat metallic green, standing almost vertically. These symptoms in the Ca(NO₃)₂ series, together with early withering of the outer leaves, strongly suggest potassium deficiency.

Table 1 shows the yields of dry matter in the beet, in the foliage, and in the

beet plus foliage (average per group of three pots). In both the $NaNO_3$ and the $Ca(NO_3)_2$ series, the increasing potassium applications produced increasing yields, but the differences can hardly be considered significant. It is very clear, however, that the yields with calcium nitrate are far inferior to those with sodium nitrate. The extent of this difference is particularly striking, in view of the fact that addition of 1650 mgm. K to the $Ca(NO_3)_2$ could not bring the total yield up to that of 525 mgm. K plus $NaNO_3$.

Experiment 3

As the Brenchley pots employed in the preceding experiments did not give complete satisfaction for beet culture, a special pot was designed for use in 1939. This not only was larger but also regulated the water supply according to an improved principle. In contrast with the Brenchley pots, in which the water was poured on a layer of silex covering the soil surface, the new pots were provided with a cylindrical ring of silica sand around the plant, to which water could be added. This affords an even penetration of water into the soil without disturbing the structure. Moreover, the new pots were twice as large (containing 13 kgm. soil plus 3 kgm. silica sand), and consequently the soil moisture was less subject to fluctuations. The pot construction is shown in figure 2.

The basic fertilizer consisted of 4.8 gm. $CaHPO_4 \cdot 2H_2O$, 2.2 gm. $MgSO_4 \cdot 7H_2O$, 0.22 gm. $MnSO_4 \cdot 4H_2O$, and 0.8 cc. a 5 per cent solution of $FeCl_3$. Again the moisture content was maintained at 60 per cent of the water-holding capacity. All pots were in quadruplicate. The following nitrates were compared: $NaNO_3$, $Ca(NO_3)_2$, and a mixture of NH_4NO_3 with $CaCO_3$. The quantity of nitrate added per pot was the equivalent of 5000 mgm. nitrogen, half as a basic fertilizer and half as a top-dressing. As in the preceding experiment, each series included increasing quantities of K, as KCl, applied as follows one fourth as a basic application and three fourths in the form of a top-dressing: (a) No K; (b) 918 mgm. K; (c) 1836 mgm. K; (d) 2754 mgm. K; (e) 3672 mgm. K. These stages are approximately comparable with those of the preceding experiment and run, therefore, from low to very high.

At first, the beets in the NH_4NO_3 + $CaCO_3$ series grew more rapidly than the others, and some effect of the K stages was evident in the $NaNO_3$ and in the $Ca(NO_3)_2$ series, where the plants growing without K addition and with 918 mgm. K were slightly more advanced than those with larger additions of K. The situation changed gradually. The plants in the $Ca(NO_3)_2$ series soon fell behind, and the advantage held by the NH_4NO_3 + $CaCO_3$ series was gradually converted into a disadvantage; as a result, the plants in the $NaNO_3$ series were definitely superior to those in the other series by the middle of the growing period. As in the previous experiment, the $Ca(NO_3)_2$ treatment developed a special type of plant, particularly distinguished by the dark, almost metallic green color of the foliage. Exactly the same type was now found in the plants treated with NH_4NO_3 + $CaCO_3$. The influence of the increasing K dressings became, in time, even less apparent than in experi-
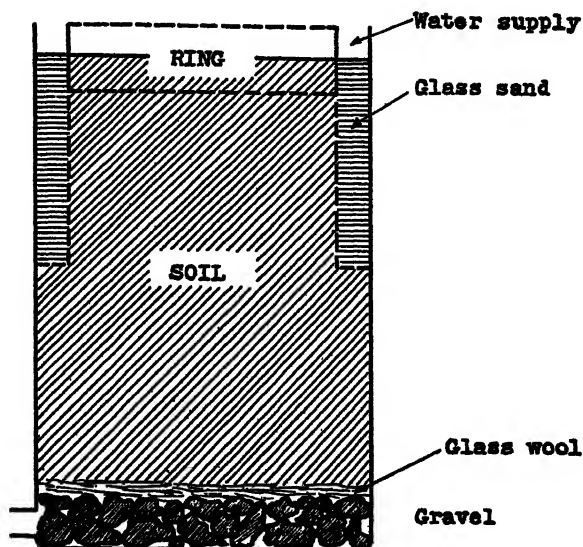
FIG. 2. SPECIAL POT FOR BEET CULTURE

Water applied to the cylindrical ring of glass sand around the plant moistens the soil uniformly without disturbing the structure

TABLE 2

Average yields of dry matter, in grams per pot, of beet plants grown with NaNO₃, with Ca(NO₃)₂, and with NH₄NO₃ + CaCO₃, to which were added increasing quantities of potassium

K APPLICA-TIONS .... *mgm.*	0	918	1836	2754	3672
Beet:					
NaNO₃........	91.9 ± 7.2	106.4 ± 7.8	99.0 ±7.3	90.6 ± 2.4	106.8 ±3.1
Ca(NO₃)₂......	63.3 ± 1.6	52.4 ± 4.7	50.5 ±3.9	57.4 ± 8.4	59.8 ±2.5
NH₄NO₃ + CaCO₃......	54.0 ± 4.9	56.9 ±11.3	63.9 ±8.1	70.3 ±11.0	54.0 ±4.9
Foliage:					
NaNO₃........	58.6 ± 3.7	62.0 ± 6.7	59.7 ±5.6	65.0 ± 4.9	61.8 ±3.8
Ca(NO₃)₂......	47.7 ± 1.7	47.4 ± 2.3	42.7 ±3.4	45.9 ± 4.3	48.0 ±2.8
NH₄NO₃ + CaCO₃......	46.5 ± 3.0	50.2 ± 2.8	48.6 ±2.2	55.9 ± 5.4	53.7 ±5.0
Total:					
NaNO₃........	150.5 ±10.3	168.3 ±11.5	158.7 ±4.4	155.7 ± 6.4	168.6 ±1.7
Ca(NO₃)₂......	110.9 ± 1.8	99.8 ± 3.2	93.2 ±5.9	103.3 ±11.8	107.8 ±5.3
NH₄NO₃ + CaCO₃......	100.5 ± 5.8	107.1 ±10.3	112.5 ±8.8	126.2 ±15.4	107.7 ±9.1

ment 2. If anything, the plants receiving little K (a, b, and c) were slightly superior to those receiving much (d and e), whether in the NaNO₃, the Ca(NO₃)₂, or the NH₄NO₃ + CaCO₃ series. This suggests that the typical

symptoms found in the last two series were the result of an unsuitable equilibrium of ions rather than of K deficiency. We shall revert to this question, in connection with analyses, in a subsequent paper of this series.

Table 2 shows the yields of this experiment, each figure representing the average of quadruplicate pots. Like the type of plant growth, the yields, in general, appear to have been but little affected by the increasing applications of potassium. There is, however, a significant difference in yield between the $NaNO_3$ series, on the one hand, and the $Ca(NO_3)_2$ and $NH_4NO_3 + CaCO_3$, on the other. The results suggest that the effect of the nitrate fertilizers dominates and that, strictly speaking, the K application produced yield increases only with $NH_4NO_3 + CaCO_3$. The question arises: Why does $NH_4NO_3 + CaCO_3$ produce a type of plant which strongly resembles that produced by $Ca(NO_3)_2$ and which is also comparable in its low yield. Because of the presence of $CaCO_3$ in addition to the NH_4NO_3, the question is more complicated than that of merely the anion in the nitrate compound, for it is not known whether the $CaCO_3$ penetrates *into* the soil or remains on the surface. A plausible explanation can be given for the similarity in effect of ammonium nitrate and calcium nitrate: Ammonium nitrate as a fertilizer participates in all kinds of interchanges. The NH_4 ion interchanges with the Ca ion of the soil complex, and as a result calcium nitrate is formed. The interchanged NH_4 is converted later into nitrate by the nitrification process; therefore, in soils sufficiently rich in Ca, further calcium nitrate is formed. Consequently, it is not surprising that $NH_4NO_3 + CaCO_3$ exercises on beets an effect similar to that of $Ca(NO_3)_2$, because most of the mixture is converted into $Ca(NO_3)_2$.

CONCLUSIONS

From the point of view of economic fertilizing, it makes an enormous difference which secondary ion is present in addition to the nitrate ion. The yield of beets is substantially higher with $NaNO_3$ than with $Ca(NO_3)_2$. In experiment 1, for instance, $NaNO_3$ produced increased yields ranging between 47 and 170 per cent; in experiments 2 and 3, increased yields of 65 per cent and 75 per cent respectively, $Ca(NO_3)_2$ and $NH_4NO_3 + CaCO_3$ giving approximately equal yields. The most important conclusion to be drawn from these experiments is that the effect of the secondary ions was as important as the effect of the so-called main component, nitrate.

Supplementary field observations indicate that the effect of the secondary ions is most pronounced in weakly buffered, that is, sandy, soils. The effect is not so great on clay soils, although not negligible from the standpoint of economic fertilizer practice.

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INFLUENCE OF MICROORGANISMS ON SOIL AGGREGATION AND EROSION: II[1]

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· In a previous paper (8) consideration was given to the role of microorganisms in bringing about soil aggregation as determined by the use of artificial and natural soils, simple carbohydrates and complex plant materials, and pure and mixed cultures of microorganisms. It was found that the extent and duration of the aggregation effect and the time required for it to reach a maximum depended upon the nature of the soil, the type of organisms concerned, and the chemical nature of the organic material used. The aggregating effects were greatest in the natural soils; a mixed soil population was most effective in bringing this about. With respect to the aggregating influence of complex organic materials, it was found that the greater the percentage of readily available constituents in organic material undergoing decomposition, the greater was the effect upon soil aggregation. For example, alfalfa brought about greater aggregation than stable manure, which, in turn, was more effective than low-moor peat.

It seemed desirable to expand this work to cover proteins and lignins, which are considered (18) as humus-forming materials, as well as complex plant materials and humus forms in natural soils, and to study the effect of lime upon the binding of the finer soil particles, under the influence of microorganisms. Since this paper is to be considered as a second part of the previous one (8), the references reported there will not be duplicated here.

HISTORICAL

Various investigators have established the fact that soil aggregation is greatly influenced by the crop grown and the nature of the plant residues added to the soil (1, 17, 19). Hay, consisting largely of timothy, was found (5) to leave the soil in a better physical condition than corn, wheat, or clover. The aggregation of soils low in organic matter was more pronounced as a result of addition of organic residues than was the case with soils high in humus (12).

A study of soil aggregation and soil erosion, as influenced by treatments with lime alone and in combination with organic materials, has been the object of several investigations during recent years. Heretofore, it was generally ac-

cepted that lime contributes to the formation of stable aggregates in the soil, but these investigations have shown that the effect of calcium upon soil aggregation may not be so important as was formerly believed. Baver (2, 3) says that the physical properties of H-saturated and Ca-saturated soils and colloids are similar. Lutz (7) has shown that H-clay membranes were a little more permeable than Ca-clay membranes; in these studies, the exchange complex of the clay was saturated with hydrogen by electrodialysis and with calcium by addition of $Ca(OH)_2$ to suspensions of the electrodialyzed colloidal material. Peele (15) found that the addition of lime to Cecil clay under field conditions tended to reduce permeability and to exert a slight dispersing effect on the soil aggregates. Baver (2) suggested that calcium may influence granulation indirectly through its effect upon organic matter or biological activity. The role of calcium in chernozem formation and its effect upon granulation through its interaction with the soil humus has been emphasized particularly by Russian pedologists (6). Metzger and Hide (9) reported that limed soil in which sweet clover and red clover were growing left the soil more aggregated than unlimed soil growing the same crops, but, unlimed fallow soil was as well aggregated as the corresponding limed fallow soil.

Bradfield (4) emphasized that the best structure is usually found in virgin soils. Interfaces were said to be created on the surface of soil granules. These interfaces were considered as organic products of the plant roots and of the microorganisms feeding upon them. In undisturbed soil, these organisms build up a fairly stable interface, the so-called "water-resistant aggregates." Myers and McCalla (13) found that maximum aggregation occurred a few days after the numbers of bacteria in the soil reached a maximum; they concluded that bacteria play an indirect role in aggregate formation and that the products of microbial activity are apparently the main factors involved. Other investigators have stressed the importance of microorganisms in the process of soil aggregation [see (8)].

The erodibility of the soil has been found to be correlated with the state of its aggregation [see (8)]. Rainwater enters a well-aggregated soil more readily than a poorly aggregated soil, as a result of which there is less runoff and consequently less erosion. Because of this relationship between erosion and soil aggregation, the influence of various treatments on the latter has been used as a measure of the relative effect of these treatments upon the erodibility of the soil (14). Soil aggregation is, however, important not only from the point of view of resistance to erosion: a granular structure offers less resistance to root penetration, allows free intake and retention of rainfall, thus providing a more adequate water supply for the plants, and ensures better air circulation.

When plant and animal residues are added to the soil, the microbiological population is immediately set in motion, resulting in rapid destruction of the organic materials. Various fungi and actinomycetes produce a network of mycelium which penetrates the soil mass and tends to bind the soil particles together. Bacteria produce slimes and gums which tend to cement the soil

particles together.   A great variety of decomposition products and synthesized compounds, produced by the microorganisms, interact chemically or physically with the inorganic soil particles, resulting in increased aggregation.   Since organic materials differ considerably in chemical composition and result in the growth of different microbial populations, the influence of one type of material upon soil aggregation will differ from that of another.   Lime may also affect soil aggregation in more than one way: it influences the development of specific microbes, and it affects the inorganic and organic colloids of the soil.

The influence of microorganisms upon soil aggregation thus involves several problems, among which the following are of particular significance:

The mechanical effect of microbes, because of their capacity to act as direct binding agents of soil particles

The physical and chemical effects of substances produced by microbes, resulting in the aggregation of soil constituents

The products of decomposition of organic matter, which are most active in bringing about the binding or the aggregation of soil particles, and the formation of such products at different stages of decomposition

The effects of additions of different types of organic matter to the soil

The influence of certain inorganic substances, such as lime, upon the aggregation of soil particles by microorganisms and their products.

EXPERIMENTAL

Methods

A method designated as the "pipette method," a modification of the one previously described (8), was used to determine the effects of various organic matter treatments on the aggregation of the soil.   This method may be outlined as follows:

Soil in 25- or 50-gm. portions, depending on the texture, was placed in distilled water and allowed to stand for 15 minutes.   The suspension was then transferred to a 500-ml. graduate, filled to the mark with distilled water, and shaken end over end 10 times.   The graduate was allowed to stand until a 25-ml. sample pipetted at a depth of 5 inches consisted of silt and clay particles, i.e., particles having a maximum diameter of 50 μ.   The settling time, calculated according to Stokes' law, was approximately 1 minute when the temperature of the water was 21°C.   For the calculation, the density of the soil was assumed to be 2.70.   The aliquot was evaporated to dryness in a weighed evaporating dish and weighed.   The weight of the particles having diameters of 50 μ and less was calculated on the basis of the original 50-gm. portion of soil and is referred to as unbound material.   When moist soil or when less than 50 gm. of material was used for analysis the weight of the unbound material was corrected to correspond to 50 gm. of dry soil.   The percentage aggregation of the silt and clay fractions of the soil was then calculated, on the assumption that the control had a value of 0.

The pipette method is similar to Middleton's (10) "dispersion ratio," which is the ratio of the weight of silt + clay, determined in a manner similar to that described above, to the weight of these fractions determined by mechanical analysis.   As a result of studies dealing with the properties of soils which influence erosion, Middleton pointed out that the dispersion ratio "seems to have

some bearing on the erosive characteristics of the soil without regard to the other properties," and concluded that the dispersion ratio is "probably the most valuable single criterion in distinguishing between erosive and nonerosive soils." If the silt and clay particles are not bound into water-stable aggregates they are the first to be eroded from the soil (7, 10, 11).

In connection with certain of the soil studies, aggregate analysis of several-sized fractions was run on samples of dry soil. The details of the procedure are the same as those described for the "pipette method" except that a 1-liter cylinder was used in this case and the settling intervals were arranged so as to give the weight of the particles having effective diameters of $<50\mu$, $<20\mu$, and $<5\mu$. From these figures the percentage aggregation of the $<50\mu$, $<20\mu$, and $<5\mu$ particles was calculated on the basis of a value of 0 for the control.

Two soils, Bermudian clay loam and Collington sandy loam, were used. The first consisted of 33 per cent clay, 37 per cent silt, and 28 per cent sand; and the second, of 9 per cent clay, 8 per cent silt, and 83 per cent sand. It was considered desirable to use a soil containing as little organic matter as possible. For that reason the subsurface soil was collected. The heavy soil contained 0.33 per cent and the sandy soil 0.25 per cent organic carbon.

Because in previous experiments a mixed soil population proved to be the most effective aggregating agent, and because it represents more nearly natural conditions, a suspension of a fertile soil was used as an inoculum in nearly all cases.

The results reported are the averages of duplicate determinations. The two portions for analysis were taken from different flasks or pots receiving the same treatment rather than from the same flask or pot. Only average values are reported because the duplicates checked very well in most cases.

Effect of protein, lignin, and lime on soil aggregation

In the following studies, casein was used as a source of protein, and alkali lignin obtained from straw, as a source of lignin. Two-hundred-gram portions of soil were used. Casein and lignin were added in 2 per cent concentrations; when used in mixture, 1 per cent concentration of each was used; $CaCO_3$ was added in a concentration of 0.3 per cent.

The treated soils were placed in tumblers. The moisture content was brought to and maintained at approximately 55 per cent of saturation. The tumblers were incubated at 28°C. After 10, 25, and 50 days' incubation, the contents of two tumblers from each treatment were analyzed in the moist and in the dry state.

The aggregating effects of casein and lignin upon the sandy soil are reported in table 1. A comparison of the results with those previously obtained with sucrose as an energy source (8) indicates that the sucrose exerts a greater and more enduring aggregating effect upon the sandy soil than does the casein. It is possible that the types of organisms favored by sucrose are more effective aggregating agents than those favored by casein. Upon drying, the casein-

treated soil in every case showed a great increase in aggregation. The cementation brought about by the compounds produced through the activities of the microorganisms appeared to become irreversible upon drying and was therefore more effective in establishing water-stable aggregates.

The state of aggregation of the soil receiving 2 per cent casein was best in the moist soil after 10 days' incubation and in the dry soil after 25 days. In the soil receiving only 1 per cent casein the maximum aggregation occurred in both the moist and the dry soil at 10 days. In the dry soil a decrease in aggregation occurred more quickly than in the soil receiving a greater amount of energy material. The pH values of the soils receiving both 2 and 1 per cent casein were approximately the same throughout the experiment, but the binding was much greater in the soil receiving the larger amount of energy material.

Lignin appeared to have no aggregating effect upon the sandy soil.

TABLE 1

Effect of protein and of lignin upon the aggregation of Collington sandy loam

STATE OF SOIL	MOIST			DRY			
Incubation period.............*days*	10	25	50	10	25	50	
Treatment	Unbound material*	Bound†	Bound	Bound	Bound	Bound	Bound	pH
	gm.	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	
Control....................	6.06	0	0	0	0	0	0	6.5
Casein, 2%...............	4.35	28	26	23	51	62	47	8.4
Casein, 1% and lignin, 1%...	4.33	29	15	15	46	43	34	8.2
Lignin, 2%...............	6.10	0	0	0	0	2	0	6.4

* Weight of unaggregated silt + clay particles.

† Percentage of silt + clay particles aggregated, assuming control to have a value of 0.

The aggregating effect of similar treatments upon the clay loam soil is found in table 2. In certain respects the results are similar to those obtained with the sandy soil. The maximum binding effect occurred in the moist soil after 10 days' incubation. Thereafter the aggregation of the soil receiving 2 per cent casein decreased rapidly while that treated with 1 per cent casein + 1 per cent lignin decreased only slightly. In the moist soil, by far the greatest aggregation occurred in the soil to which 1 per cent casein + 1 per cent lignin + 0.3 per cent $CaCO_3$ were added. The same treatment minus the calcium carbonate brought about a greater aggregation than did the addition of 2 per cent casein. It is possible that a combination of the lignin and casein occurred which resulted in increased aggregation and that calcium increased the effectiveness of the complex, or that the larger amount of ammonia produced in the soil receiving 2 per cent casein caused the development of a soil population which was less efficient in binding the moist soil. The calcium treatment had only a slight influence upon the aggregation of the moist soil, except where casein and lignin were also added.

As was the case with the sandy soil, drying greatly increased the aggregation of the soil treated with 2 per cent casein. At all three periods of incubation approximately 50 per cent of the silt and clay particles were aggregated. The drying process increased the binding of the casein + lignin treated soil only slightly. The difference in the behavior of the two treatments indicates that different cementing substances were produced.

Calcium carbonate alone and in combination with lignin caused a dispersion of the dry soil at first; however, after 50 days' incubation this dispersing effect tended to disappear.

TABLE 2

Effect of protein, lignin, and lime upon the aggregation of Bermudian clay loam

State of Soil	MOIST			DRY			
Incubation period ....days	10	25	50	10	25	50	
Treatment	Unbound material	Bound	Bound	Bound	Bound	Bound	Bound	pH
	gm.	per cent	per cent	per cent	per cent	per cent	per cent	
Control....................	16.1	0	0	0	0	0	0	4.7
CaCO₃, 0.3%..............	16.1	0	6	6	−11	−3	−1	6.0
Casein, 2%...............	11.6	29	14	8	51	55	44	6.7
Casein, 2% and CaCO₃, 0.3%.	11.5	29	14	6	53	55	51	7.2
Casein, 1% and lignin, 1%...	11.1	31	27	23	35	41	41	5.7
Casein, 1%, lignin, 1% and CaCO₃, 0.3%.............	8.9	45	35	35	35	47	46	6.3
Lignin, 2%...............	16.8	−3	2	2	2	7	12	5.0
Lignin, 2% and CaCO₃, 0.3%.	16.6	−3	6	0	−11	−3	0	6.1

Aggregating effect of microorganisms upon various silt and clay fractions of Collington sandy loam with complex organic materials as energy sources

To study the influence of complex organic substances on the aggregation of several fractions of the smaller soil particles, two series of 200-gm. portions of Collington sandy loam were treated with 2 per cent concentrations of alfalfa, stable manure, or lowmoor peat.

The organic materials were dried and finely ground before they were used. The mixtures were placed in 500-ml. Erlenmeyer flasks, and the moisture content was adjusted to 55 per cent of saturation. The flasks were sterilized in the autoclave at 15 pounds pressure for 2 hours. Each flask of one series was inoculated with 1 ml. of a suspension of *Aspergillus niger* spores and the flasks of the other series with 1 ml. of a soil suspension. After 20, 50, and 90 days' incubation, duplicate flasks from each treatment were dried at 50°C., and the soil was passed through a 3-mm. sieve and analyzed. The results are presented in table 3. In both series, alfalfa brought about the greatest aggregation, manure was somewhat less effective, and peat exerted the least aggregating

influence.   The mixed soil population influenced the physical properties of the soil more favorably than did *A. niger*.

With alfalfa as a source of energy, *A. niger* brought about in every case a greater percentage aggregation of the $<50\mu$ particles than of either the $<20\mu$ or $<5\mu$, and similarly a greater percentage aggregation of the $<20\mu$ than of the $<5\mu$ particles.   In other words, *A. niger* in this case caused a greater percentage aggregation of the silt particles than of the clay.   In the soil receiving manure, *A. niger* aggregated a larger percentage of the silt than of the clay particles after 20 days, but the percentage aggregation of all three fractions

TABLE 3

Aggregating effect of microorganisms upon various silt and clay fractions of Collington sandy loam with complex organic materials as energy sources

INCUBATION PERIOD........*days*		20			50			90		
Fraction.......................		$<50\mu$	$<20\mu$	$<5\mu$	$<50\mu$	$<20\mu$	$<5\mu$	$<50\mu$	$<20\mu$	$<5\mu$
Inoculation	Energy source[a]	Weight	Ag.[b]	Ag.	Ag.	Ag.	Ag.	Ag.	Ag.	Ag.
		gm.								
A. niger	Control	6.35	0	0	0	0	0	0	0	0	0
	Alfalfa	3.20	49	45	31	57	52	36	52	46	30
	Manure	4.84	24	22	10	29	41	31	32	36	40
	Peat	6.14	4	9	3	19	31	30	15	23	34
Soil suspension	Control	6.31	0	0	0	0	0	0	0	0	0
	Alfalfa	2.74	57	61	61	71	77	74	68	68	64
	Manure	4.32	32	41	27	44	54	56	40	47	50
	Peat	5.82	8	17	18	15	29	34	13	20	25

[a] All organic materials used in 2 per cent concentration.
[b] Ag. — Percentage aggregation.

was similar after 50 and 90 days' incubation.   Peat had little effect on any of the soil particles after 20 days, but it exerted a definite influence, especially upon the smaller soil fractions, after 50 and 90 days.

The mixed soil population effected a different type of aggregation of the various soil fractions than was produced by *A. niger*.   With alfalfa as an energy source, the percentage aggregation of the three fractions was approximately the same at each incubation period.   After 90 days' incubation, for example, the percentage aggregation of the $<50\mu$, $<20\mu$, and $<5\mu$ particles was 68, 68, and 64, respectively.   With manure as an energy source, there was a tendency for relatively greater aggregation among the smaller soil particles; with peat, there was definitely a greater percentage aggregation of the smaller than of the larger particles.   As the amount of available energy material in the organic matter used increased, the size of the particles bound into water-stable aggregates increased.

Influence of lime and complex organic materials upon aggregation of Bermudian clay loam

To study the effect of lime on the aggregating action of organic materials during decomposition, 1-kgm. portions of dried and screened Bermudian clay loam were treated in duplicate with alfalfa, wheat straw, stable manure, low-moor peat, and lime, in concentrations similar to those used in the foregoing

TABLE 4

Aggregating effect of lime and complex organic materials upon Bermudian clay loam

INCUBATION PERIOD....................days	20		50	100	150	210	
Treatment*	Unbound material	Bound	Bound	Bound	Bound	Bound	pH
	gm.	per cent	per cent	per cent	per cent	per cent	
Moist soil							
Control..........................	19.9	0	0	0	0	0	
CaCO₃............................	19.4	3	9	9	16	30	
Alfalfa...........................	13.1	35	23	15	19	39	
Alfalfa + CaCO₃..................	13.3	34	30	39	38	42	
Straw†...........................	15.9	21	20	15	15	37	
Straw† + CaCO₃..................	14.1	29	41	38	39	42	
Manure..........................	16.8	16	16	13	26	31	
Manure + CaCO₃.................	16.6	17	25	28	34	37	
Peat............................	20.0	0	0	0	5	14	
Dry soil							
Control........................	23.5	0	0	0	0	0	4.6
CaCO₃...........................	23.5	0	0	2	0	5	6.0
Alfalfa.........................	14.8	38	31	29	26	30	4.8
Alfalfa + CaCO₃.................	14.8	38	35	36	29	32	6.0
Straw†..........................	15.4	35	40	35	32	34	4.7
Straw† + CaCO₃.................	14.2	40	45	43	36	35	6.0
Manure..........................	19.8	17	21	18	20	17	4.7
Manure + CaCO₃.................	19.0	19	24	28	25	20	6.0
Peat............................	23.4	0	5	7	3	0	4.7

* CaCO₃ added, 0.3 per cent; organic materials, 2 per cent, on dry basis.
† 0.05 per cent urea was added with the straw.

experiments. The treated soils were placed in pots, and the moisture content was adjusted to and maintained at approximately 55 per cent of saturation. Between the 150- and 210-day incubation periods, however, the soil was allowed to dry out considerably and was then remoistened. No water was added to the pots for at least one week before aggregate analyses were made.

After 20, 50, 100, 150, and 210 days' incubation at 28°C. the variously treated soils were analyzed in the moist and dry states by the pipette method. The entire contents of each pot were removed and mixed well before the sample

was taken for analysis. Samples of the dry soil were also analyzed to determine the relative aggregation of several fractions of the smaller soil particles, namely, $<50\mu$, $<20\mu$, and $<5\mu$.

The results of these determinations are given in tables 4 and 5. The analyses of the moist soil show that after 20 days the organic materials alone, with the exception of peat, had a considerable aggregating effect upon the soil, the influence of alfalfa and straw being greater than that of manure. Lime alone brought about virtually no aggregation of the soil at this time, and lime together with alfalfa and manure had no additional effect over the organic treat-

TABLE 5

Aggregating effect of lime and complex organic materials upon various silt and clay fractions of Bermudian clay loam

Incubation Period..days	20				50			100			150			210		
Fraction........	$<50\mu$	$<20\mu$	$<5\mu$		$<50\mu$	$<20\mu$	$<5\mu$	$<50\mu$	$<20\mu$	$<5\mu$	$<50\mu$	$<20\mu$	$<5\mu$	$<50\mu$	$<20\mu$	$<5\mu$
Treatment*	Weight	Ag.†	Ag.	Ag.	Ag.	Ag.	Ag.	Ag.	Ag.	Ag.	Ag.	Ag.	Ag.	Ag.	Ag.	Ag.
	gm.															
Control......	21.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CaCO₃......	22.4	−5	3	27	−3	17	67	3	19	82	5	29	75	9	27	90
Alfalfa......	12.2	43	34	30	32	30	30	35	31	30	33	33	36	30	34	44
Alfalfa + CaCO₃.....	12.1	44	48	50	38	35	35	36	42	42	37	46	54	34	42	53
Straw‡......	12.4	42	36	40	42	35	30	40	34	34	41	41	37	37	36	37
Straw‡ + CaCO₃....	12.6	41	46	47	48	43	42	43	38	41	43	46	47	36	39	50
Manure.....	18.5	14	15	15	18	11	17	22	16	18	25	26	29	17	22	35
Manure + CaCO₃....	18.2	15	20	32	20	21	34	28	28	30	28	35	40	17	22	35
Peat........	20.4	4	8	12	3	3	9	2	4	7	5	17	24	0	0	7

* CaCO₃ added, 0.3 per cent; organic materials, 2 per cent, on dry basis.

† Ag. = Percentage aggregation.

‡ 0.05 per cent urea was added with the straw.

ments alone. Straw and lime together, however, brought about a slightly greater aggregation than straw alone. As the incubation period increased, the aggregating effect of alfalfa and of straw decreased a little but that of manure and the three organic materials used with lime remained about the same or increased slightly. As a result of this, the state of aggregation of the soils treated with organic matter and lime was better than that of the soils receiving organic matter alone. The difference was consistently greatest in the straw-treated soil.

The aggregating action of manure gradually increased and was greatest after 150 and 210 days' decomposition. Up to the 150 days, peat had no aggregating effect.

Because of the drying of the soils between the 150- and 210-day incubation periods, the state of aggregation of those soils that received organic materials increased considerably. This drying process probably had a partial sterilization effect, which resulted in increased microbial activity. The aggregation of the soil to which lime was also added was improved only slightly, however, by the drying process.

The effect of lime alone upon aggregation, as measured in moist soil, was interesting: virtually no effect was evident after 20 days, but after 50 days a small increase in aggregation occurred; after 100 days the percentage aggregation was the same as after 50, but after 150 days it had increased to 16 per cent and after 210 days to 30 per cent. Lime alone thus had a definite effect upon the aggregation of the silt and clay particles of the soil as shown by the analysis of the moist soil, but this influence was very slow in developing.

The analyses of moist soil did not agree in all cases with those obtained with the dry soil. After 20, 50, and 100 days' incubation, drying of the soil increased aggregation in nearly every case. With the exception of the 20-day period, the increase due to drying was much greater in the soil samples receiving organic matter alone than in those receiving lime as well. Consequently the differences in the aggregation between the organic matter alone and the organic matter + lime treatments were not so great as in the moist soil. After 150 days in all except the alfalfa and straw treatments, and after 210 days in all treatments, drying resulted in a small decrease in aggregation. Although the analyses of the moist soil showed that lime alone exerted a gradually increasing effect upon the aggregation of the silt and clay particles, this effect disappeared after the soil had been dried.

In most instances, as shown in table 5, the percentage aggregation of the $<50\mu$, $<20\mu$, and $<5\mu$ particles, for each organic matter treatment and after various incubation periods, was similar. For example, the aggregation values for the three fractions in the alfalfa-treated soil after 50 days' incubation were 32, 30, and 30 per cent, respectively. After 100 days' incubation, however, the aggregation of the smaller fractions in the organic matter plus lime treatments was greater than that of the larger particles: after 150 days, for instance, the aggregation of the $<50\mu$ particles of the alfalfa + lime treated soil was 37 per cent; that of the $<20\mu$, 46 per cent; and that of the $<5\mu$, 54 per cent.

Lime influenced the various soil fractions differently. It brought about no aggregation of the $<50\mu$ fraction and virtually none of the $<20\mu$ fraction after 20 days, but it caused a definite aggregation of the $<5\mu$ particles (27 per cent) at this period. After 50 days, the aggregation of the $<5\mu$ particles had increased to 67 per cent and to 17 per cent for the $<20\mu$ particles. After 210 days' incubation, 90 per cent aggregation of the $<5\mu$, and 27 per cent of the $<20\mu$ particles occurred, but no appreciable aggregation of the $<50\mu$ particles was evident. In time, the lime brought about the aggregation of the $<5\mu$ particles into water-stable aggregates having effective diameters between 5 and 50μ. It also aggregated some of the $<20\mu$ particles into aggregates having

diameters between 20 and 50μ. Since larger aggregates were present in the moist, lime-treated soil, it is evident that the drying process broke these up into smaller aggregates.

Although peat exerted a negligible influence upon the <50μ particles it had a small binding effect upon the smaller ones. After 150 days' incubation, peat appeared to have exerted a very marked effect upon the smaller particles, but part of this influence was due to the fact that the moisture content of the peat-treated soil was slightly lower than that of the control at this period.

In previous experiments it was noted that the moisture content had a considerable effect upon the aggregation of the silt and clay particles when the moist soil was used for analysis. This influence, especially in Collington sandy loam, tended to disappear after the soil had been dried. An examination of the results for the unaggregated <20μ and <5μ particles in the control soil portions of the foregoing experiment, in comparison with the original moisture contents for the five incubation periods, indicates that the original moisture content influenced the aggregation of these small soil particles even after the soil had been dried in the oven at 50°C. This influence is evident from the following data:

INCUBATION	ORIGINAL MOISTURE CONTENT	<20μ	<5μ
days	*per cent*	*gm.*	*gm.*
20	23.3	8.50	2.44
150	23.1	8.46	2.40
50	21.2	7.35	2.09
210	20.2	7.60	2.08
100	20.0	7.22	2.02

DISCUSSION

Investigation of the aggregating influence of microorganisms upon soil particles when simple and complex organic materials are added further emphasizes the fact that microbes play an important role in the aggregation of the soil fractions and consequently in conserving the soil from removal by erosion. The extent and duration of the aggregating effect and the time required for it to reach a maximum were found to depend to a large extent upon the nature of the substrate.

In moist clay loam, casein + lignin brought about considerable aggregation, which was further increased by the addition of lime. This effect was greater than that of casein alone or of casein with lime. It is possible that there was some combination of lignin with casein, and that this combination was more active in establishing stable aggregates than were the organic cementing substances produced where casein alone was added. Calcium increased the effectiveness of this casein-lignin complex. Waksman and Iyer (18) found that lignin depressed decomposition of protein and that this influence was due to an

interaction of the lignin with the protein. Another possibility is that where casein alone was added (2 per cent) more ammonia was produced than where casein (1 per cent) and lignin were added, and that this resulted in the development of a soil population which was less efficient in binding the moist soil. After the soil had been dried, however, the 2 per cent casein treatment produced the greatest aggregation. The difference in the behavior of the two treatments in the moist and dry states suggests that different cementing substances may have been concerned.

When complex organic materials were used as sources of energy for the soil microbes, it was found that the extent of aggregation depended upon the amount of readily decomposable substances in the material used. Straw and alfalfa contain considerable quantities of cellulose and hemicelluloses, and alfalfa contains much protein also. Such plant materials, which are readily attacked by microbes, produced the greatest aggregation of the soil. Manure, which is partly decomposed material, brought about somewhat less aggregation. Lowmoor peat and lignin, which contain very little readily decomposable organic matter, did not materially influence the aggregation of the soil. When peat was sterilized, however, it had a slight aggregating effect; the sterilization process evidently made some of the material in the peat available to the micro-organisms or altered certain compounds so that they reacted with the inorganic soil particles and brought about some aggregation.

Lime alone had a definite influence upon the silt and clay particles of Bermudian clay loam; its addition resulted in considerable aggregation of the particles of the moist soil $<50\mu$ in size. This effect was very slow in developing, however, and it decreased considerably when the soil was dried. After incubation for 10 days, there was some dispersion in the dry soil treated with calcium carbonate, but the smaller fractions continued to become aggregated gradually until, after 210 days' incubation, most of the $<5\mu$ and a large part of the $<20\mu$ particles were bound into aggregates. The diameters of these aggregates were 50μ or less. It appears that the lime alone slowly brought about a considerable aggregation of the silt and clay particles, many of the aggregates being larger than 50μ. The drying process broke up these granules into smaller ones, most of which were from 5 to 20μ in size. Since the samples of Bermudian clay loam used for these studies contained only 0.5 per cent organic matter and since the influence of the additions of calcium carbonate was so marked and consistent, it would be difficult to ascribe the results to the influence of calcium on biological activities. These results do not agree with those obtained by Peele (15), who found that the addition of lime caused a decrease in the number of aggregates 20 to 40μ in size and an increase in the number of 10 to 20μ particles of Cecil clay loam. It is likely that the results are due to differences in the two soils.

When lime was added together with the organic materials it increased aggregation of the clay loam soil more than did either the organic materials alone or the lime alone. In all cases the effect of lime was much more evident in the moist soil. It is possible that the calcium carbonate made the organic cement-

ing substances more effective in the moist state or that its presence caused the formation of a different type of cementing material. As evidenced by the effects of lime when used alone with the soil, it is probable that the direct influence of lime upon the inorganic soil particles was also a contributing factor.

Determinations of the aggregation of several soil fractions indicated that when organic materials containing small amounts of readily decomposable materials were incorporated with the soil, only the small soil particles were aggregated, and these only to a limited extent. On the other hand, substances containing large amounts of energy material aggregated the larger particles as well as the smaller ones.

The aggregating effects brought about by the activities of soil microorganisms persisted for considerable periods. Even after 210 days' incubation, at optimum moisture conditions, lime and organic materials still exerted a marked effect upon the aggregation of the silt and clay soil particles. The maximum aggregating effects in the soils in most of the experiments occurred, however, after an incubation period of 10 to 25 days.

Microorganisms undoubtedly play a very important role in aggregating the soil particles. This is brought about through the activity of the organisms in decomposing the organic materials that find their way into the soil. In the early stages of decomposition, some of the aggregating effect may be due to an actual sticking or binding together of the soil particles by fungus and actinomycete filaments and by the slimes and gums produced by various bacteria. Aggregation is also brought about by physical and chemical interactions between the inorganic soil particles and the synthesized and decomposition products resulting from microbial activity. In the later stages of decomposition it is probable that physicochemical aggregation is the more important of the two types.

<div align="center">SUMMARY</div>

The results of investigations on the role of microorganisms in bringing about aggregation of the fine soil particles have been reported. Such aggregation may be expected to have an important bearing on soil erosion.

Two field soils, Bermudian clay loam and Collington sandy loam, were studied. Various organic substances were added, with and without lime. A mixed soil population was used as the inoculant. After certain periods of incubation the soils were tested by a pipette method to determine the aggregating effects of the activities of the microorganisms upon the silt and clay particles.

The action of microorganisms was found to result in a marked aggregation of the soil particles. The extent of aggregation depended upon the nature of the organic and inorganic materials added.

Alfalfa and straw were more effective than manure, which, in turn, was more effective than peat or lignin, in establishing aggregates. Complex organic materials together with lime maintained a better state of aggregation of the clay loam soil than did the organic substances alone. Lime alone exerted a

small and gradually increasing effect upon the silt and clay particles of the moist soil. This effect was not so apparent after the soil was dried. The dried soil receiving lime showed an increase in the percentage of very small aggregates only.

Lignin and casein together produced greater aggregation in the clay soil than did casein alone, as determined by tests on the moist soil. After the soil was dried, the effects of casein alone appeared to be greater than the effects of casein and lignin used in combination.

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THE INTERACTION OF HIGHER PLANTS AND SOIL MICRO-ORGANISMS: III. EFFECT OF BY-PRODUCTS OF PLANT GROWTH ON ACTIVITY OF FUNGI AND ACTINOMYCETES[1]

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The chemical composition of the tissues of cultivated plants resistant to certain soil-borne diseases has been considered by various investigators. A number of chemical compounds have been isolated from resistant plants and their fungicidal and bactericidal properties demonstrated. The literature contains no records, however, concerning the influence of by-products of the growth of resistant varieties of cultivated plants on the activity of soil micro-organisms. In previous reports of this series (12) it was shown that micro-organisms are more abundant in the rhizosphere of cultivated plants in the seedling stage than in the same soil distant from the roots. Furthermore, a comparison of susceptible and resistant varieties of flax and tobacco indicated that varieties of flax susceptible to *Fusarium lini*, and tobacco susceptible to *Thielaviopsis basicola* harbored in their rhizosphere a more dense microbial population than did the corresponding resistant varieties (13). The qualitative studies (7, 8, 18) of bacteria in the rhizosphere of the same samples showed differences in morphology, physiology, and nutritional requirements and indicated a more pronounced "rhizosphere effect" in the case of the susceptible than of the resistant plants. The results so far obtained (11, 14) suggest that the resistant varieties of the plants investigated contain in their root tissues chemical substances which when diffused or excreted into the surrounding medium depress the activity of certain soil microorganisms.

The present investigation was undertaken to study the effect of the by-products of growth of susceptible and resistant flax varieties on the activity of soil microorganisms.

EXPERIMENTAL PROCEDURE

Two varieties of flax, Bison and Novelty, resistant and susceptible respectively to *Fusarium* wilt, were grown in soil and in nutrient solution under

aseptic conditions in the greenhouse. The soil was sandy loam with a pH value of 6.5 as determined by the glass electrode. It was passed through a ⅛-inch mesh sieve, and 200 gm. was placed in each of 18 porcelain pots (4 inches in diameter). The moisture content of the soil in one half of the pots was adjusted to 60 per cent, and in the second half to 30 per cent, of total moisture-holding capacity and was maintained at these levels throughout the experiment. Six pots were sown with each variety of seed, and six pots were kept as controls. The procedure for the rhizosphere analysis was the same as that previously described (13).

Plants were grown under aseptic conditions in pint glass jars in Crone's nutrient solution with the addition of 0.004 gm. $MnSO_4$ and 0.003 gm. H_3BO_3 per liter. To prevent contamination of the solution, the jars were arranged as follows: Jars filled with nutrient solution were sealed with paraffined corks, each cork containing ten holes 4 mm. and two holes 8 mm. in diameter. The cork was then covered with a layer of nonabsorbent cotton, and glass tubes were inserted into the large holes for purpose of aeration. The small holes were plugged with glass rods of the same diameter as the holes and about 2 inches long (fig. 1, left). Another layer of cotton was placed over the glass rods and tied with string at the neck of the jar. Jars thus prepared (fig. 1, right) were autoclaved for 30 minutes at 15 pounds' pressure.

In order to obtain uncontaminated seedlings, semisolid agar (3 gm. of agar per liter of solution) was prepared from the same Crone's nutrient solution and poured into glass tubes of the same diameter as the holes in the corks or glass rods (fig. 2). The tube was plugged at one end with a rubber stopper and the medium added to three-quarters of its volume. The tubes were plugged with cotton and autoclaved for 15 minutes at 15 pounds' pressure. The "test tubes" thus prepared were cooled, and one surface-sterilized seed was introduced under aseptic conditions into each tube. After 4 to 6 days' incubation the tubes were examined macroscopically and microscopically, and contaminated seedlings were discarded.

When germinated seeds were ready for transplanting the upper layer of cotton on the jar was lifted slightly by means of sterile forceps. The glass rods (the purpose of which was to keep the holes in the cork uniform in size) were removed from the corks and the tubes with the germinated seeds inserted in their places. The tubes prior to insertion were surface-sterilized as follows: About three-quarters of the length of the tube (with the rubber stopper) was dipped into 95 per cent alcohol and flamed. The rubber stopper was then removed and the tube quickly inserted in place of the glass rod. When all ten glass rods were thus replaced, the cotton was again tightened at the neck of the jar. Jars thus prepared were placed in the greenhouse, and the aeration tubes were connected by means of sterile rubber tubes with a cylinder containing compressed air. The jars were aerated daily for 10 to 15 minutes, the air being passed through concentrated sulfuric acid and an air filter.

The seedlings, usually two to five per jar, which survived the drastic treatment of surface sterilization of the glass tubes, quickly increased in size. Be-

cause of the type of growth, the tops of the seedlings were unable to push through the upper layer of cotton; it was necessary, therefore, to tear the cotton to let them get through into the open air. Twenty-five days after being transplanted, the plants (fig. 3) were removed from the jars. The remaining solution was brought up to the original volume with sterile distilled water, filtered through a Seitz filter into sterile flasks, and used for experimental purposes.

In order to study the influence of the by-products of the growth of flax plants upon the activity of soil microorganisms an attempt was made to create an "artificial rhizosphere." For this purpose the solutions described above were allowed to diffuse through collodion membrane "sacks" into the surrounding soil. The collodion membranes were about 1¾ inches long and ¼ inch in diameter, tapering at one end to a closed point. The concentration of collodion solution was the same as that described by Asheshov (1).

The collodion membranes were prepared as follows: Glass rods about ¼ inch in diameter and 10 inches long were heated and drawn to a sharp point. Usually two rods thus prepared were used at the same time. The glass rod was dipped into collodion solution to a depth of 1¾ inches and held in the container above the level of the solution until the excess solution had dripped off. The rod was then removed from the container and to obtain an even coating the upper end was rolled slowly between the thumb and index finger. When the surface of the solution was somewhat hardened the rod was placed on a support to dry. The time taken for the same manipulation with the second rod was sufficient to allow the surface of the solution on the first rod to harden enough to be pulled off from the rod without tearing. By that time the membrane on the second rod was ready to be taken off. The membranes thus prepared were allowed to dry for 5 minutes, which was sufficient to provide suitable permeability of the membrane. Finally the membranes were washed and stored in sterile distilled water.

It was noted that membranes prepared on different days showed considerable variation in permeability. It was therefore found advisable to maintain a constant temperature and humidity in the room until the membranes were made, or to make them all on the same day.

To determine the permeability of the membranes a "permeometer" was constructed. The membranes were mounted on the tips of sterile 10-ml. pipettes. The membranes, prior to mounting, were sterilized in 95 per cent ethyl alcohol for 5 minutes and washed in sterile distilled water until alcohol-free. The pipette and the membrane were first filled with sterile nutrient solution, and the tip of the pipette was slipped into the open end of the membrane. The excess liquid which appeared at the contact point was removed by means of sterile blotting paper, and the membrane was then sealed to the pipette with the same collodion solution. A sterile 1-ml. graduated pipette filled with the same nutrient solution was fitted into the other end of the 10-ml. pipette and held in place by means of a rubber stopper.

The "permeometer" so constructed was then mounted in a vertical position

with the collodion membrane suspended in the center of the pot. The pots were filled with soil, the moisture content of which was adjusted to 60 or 30 per cent of total moisture-holding capacity (fig. 4). The rate of diffusion of the nutrient solution through the membrane into the surrounding medium, per unit of time, and under the same column of pressure was read directly on the 1-ml. graduated pipette. All membranes were tested with the per-meometer. Only those which diffused not more than 0.02 ml. of solution per hour were selected for experimental purposes.

The solutions, after growth of each flax variety, were each diffused through eight membranes; original autoclaved Crone's nutrient solution and sterile distilled water were also included as controls. The soil moisture content in half of the pots in each treatment was maintained at 60 per cent and in the remaining half at 30 per cent of total moisture-holding capacity.

On the fifteenth day of the experiment the soil attached to the membranes, or the "artificial rhizosphere," and the soil distant from the membranes, or the control soil, were analyzed by the procedure and with the media previously outlined (11, 13).

MICROBIAL POPULATION OF RHIZOSPHERE

Quantitative

The density of actinomycetes and fungi in the rhizospheres of both varieties as determined by the plating method is shown in table 1. The data indicate that the rhizosphere of the susceptible variety supported 1.8 times as dense a fungus population 'as that of the resistant variety. Furthermore, it appears that a lower moisture content of the soil tends to increase the density of micro-bial population in the rhizosphere of both varieties. The data indicate, in general, a trend similar to that previously reported (8, 13), in the abundance of the microbial population of both varieties. The counts of actinomycetes indicate no appreciable differences in the density of population between re-sistant and susceptible varieties.

Qualitative

For the qualitative studies of the fungus flora of the rhizosphere and the control soil, one plate showing good distribution of colonies was selected, and each individual colony was picked and transferred to a slant of potato dextrose agar. Some cultures were then identified as to species, others to genus.[2] The

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[2] The following fungi were isolated from the rhizospheres and from the control soil: *Mortierella elasson* Sideris and Paxton, *Mucor hiomalis* Wehmer, *M. racemosus* Fres, *Rhizopus elegans* Eidam., *R. nigricans* Ehr., *Alternaria tenuis* Nees. (group), *Aspergillus flavipes* (Bain and Sart.) Thom and Church, *A. fumigatus* Fres. (group), *A. niger* (group) van Tiegh., *A. versicolor* (Vuill) Tirab. (group), *Cephalosporium humicola* Oud., *Cladosporium herbarum* (Pers) Link., *Cylindrocarpon didymum* (Hart) Wollenw., *C. macrosporium* (Fres) Wollenw., *Fusarium bulbigenum* Cke et Mass., *F. culmorum* (W. G. Sm.) Sacc., *F. oxysporum* Schlochten-dakl, *F. solani v. martii* App. et Wr., *Helminthosporium sativum* P. K. and B., *Hymenula*

relative frequency of each genus was recorded, and the number per gram of soil and its percentage of the total fungus population were calculated.

From the data presented in table 2 it is apparent that 19 genera were recorded, of which 9 were isolated from the rhizosphere and the control soil and 10 from the rhizosphere only. The numbers in the majority of cases were higher in the rhizosphere than in the soil distant from the roots. It was also evident that certain genera including *Alternaria, Aspergillus, Cephalosporium, Fusarium, Helminthosporium,* and *Verticillium* were numerically more abundant in the rhizosphere of the susceptible variety; on the other hand, *Mucor, Cladosporium, Hymenula, Penicillium, Scolecobasidium,* and *Trichoderma* were more abundant in the resistant variety. The distribution of fungi on the percentage basis of the total counts obtained presents a somewhat different

TABLE 1

Numbers of microorganisms in rhizospheres of growing plants and in control soil

	MOISTURE CONTENT*	FUNGI†		ACTINOMYCETES	
		Number	$\frac{R}{S}$ ratio‡	Number	$\frac{R}{S}$ ratio
	per cent				
Bison................... {	60	106	1.0	9.5	1.3
	30	157	2.2	11.2	1.8
Novelty................. {	60	186	1.7	10.2	1.4
	30	276	3.8	10.0	1.6
Control soil............. {	60	108	....	7.2	...
	30	72	....	6.4	...

* Percentage of total moisture-holding capacity.

† Fungi in thousands, actinomycetes in millions, per gram moisture-free soil.

‡ $\dfrac{R}{S} = \dfrac{\text{Number of organisms in rhizosphere}}{\text{Number of organisms in control soil}}$

picture. Thus, for example, in the moist soil (60 per cent) the rhizosphere of Bison yielded 12 genera; Novelty, 15; and the control soil, only 9. *Fusarium,* in the rhizosphere of Bison, yielded a count of 4,200, amounting to 4.1 per cent of the total; Novelty 19,300, or 10.3 per cent; and the control 13,500, or 12.5 per cent. *Penicillium,* on the other hand, yielded as follows: Bison, 25,500, or 23.2 per cent; Novelty, 25,700, or 13.8 per cent; and the control, 40,500, or 37.5 per cent.

The increase in total numbers in the drier soil (30 per cent) is due to the

affinis (Fautrey and Lamotto) Wollenw., *Metarrhizium* sp., *Papularia sphaerosperma* (Pers.) von Hohn, *Penicillium chrysogenum* Thom, *P. intricatum* Thom, *P. janthinellum* Thom, *P. lilacinum,* Thom, *P. restrictum,* Gilman and Abbott., *P. terrestre,* Jensen, *Scolecobasidium constrictum,* Abbot., *Stachybotrys* sp., *Trichoderma veridi* Pers. ex Fr., *T. album* Preus, *Verticillium chlamydosporium* Goddard, *Volutella ciliata* (Alb. and Schus) Fr.

TABLE 2

Incidence of fungi isolated from rhizosphere of flax varieties and from control soil

Numbers of fungi in thousands per gram of moisture-free soil

FUNGUS	BISON						NOVELTY						CONTROL					
	60 per cent soil moisture			30 per cent soil moisture			60 per cent soil moisture			30 per cent soil moisture			60 per cent soil moisture			30 per cent soil moisture		
	No. of cultures	No. of fungi	% of total	No. of cultures	No. of fungi	% of total	No. of cultures	No. of fungi	% of total	No. of cultures	No. of fungi	% of total	No. of cultures	No. of fungi	% of total	No. of cultures	No. of fungi	% of total
Mortierella	1	4.2	4.1	…	…	…	1	6.4	3.4	…	…	…	…	…	…	…	…	…
Mucor	…	…	…	2	12.0	7.6	1	6.4	3.5	1	8.7	3.1	…	…	…	…	…	…
Rhizopus	…	…	…	…	…	…	2	12.8	6.9	…	…	…	1	6.7	6.2	1	4.8	6.6
Alternaria	2	8.5	8.1	1	6.0	3.8	…	…	…	2	17.4	6.3	1	6.8	6.3	…	…	…
Aspergillus	2	8.5	8.1	2	12.0	7.7	2	12.8	6.9	2	17.4	6.3	1	6.8	6.3	2	9.6	13.3
Cephalosporium	1	4.2	4.1	…	…	…	3	19.3	10.3	4	34.9	12.5	…	…	…	…	…	…
Cladosporium	…	…	…	3	18.1	11.5	2	12.8	6.9	2	17.4	6.3	…	…	…	…	…	…
Cylindrocarpon	1	4.2	4.1	…	…	…	1	6.4	3.5	1	8.7	3.1	…	…	…	…	…	…
Fusarium	1	4.2	4.1	1	6.0	3.8	3	19.3	10.3	6	52.3	18.8	2	13.5	12.5	2	9.6	13.4
Helminthosporium	1	4.2	4.1	…	…	…	2	12.8	6.9	3	26.2	9.4	1	6.7	6.2	…	…	…
Hymenula	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
Metarrhizium	6	25.5	23.2	1	6.0	3.8	…	…	…	1	8.7	3.1	6	40.5	37.5	7	33.6	46.7
Penicillium	…	…	…	8	48.5	30.9	4	25.7	13.8	4	35.0	12.5	…	…	…	…	…	…
Papularia	…	…	…	1	6.0	3.8	1	6.4	3.4	…	…	…	…	…	…	…	…	…
Scolecobasidium	…	…	…	1	6.0	3.9	…	…	…	…	…	…	…	…	…	…	…	…
Stachybotrys	3	12.8	12.0	…	…	…	1	6.4	3.5	2	17.4	6.2	1	6.8	6.3	…	…	…
Trichoderma	1	4.2	4.1	5	30.4	19.4	1	6.4	3.5	1	8.7	3.1	2	13.5	12.5	3	14.4	20.0
Verticillium	2	8.5	8.0	…	…	…	2	12.8	6.9	3	26.2	9.4	1	6.7	6.2	…	…	…
Volutella	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
Undetermined	4	17.0	16.0	1	6.0	3.8	3	19.3	10.3	…	…	…	…	…	…	…	…	…
Total	25	106	100	26	157	100	29	186	100	32	279	100	16	108	100	15	72	100

fact that fewer genera were isolated as compared with the moist soil, thus increasing the incidence of the individual genus. In this case the rhizosphere of Bison yielded 11 genera; Novelty, 13; and the control soil, 5.

MICROBIAL POPULATION OF ARTIFICIAL RHIZOSPHERE

Quantitative

The data presented in table 3 indicate that the density of the microbial population in the soil in the vicinity of the collodion membranes, or artificial rhizosphere, was higher than in the control soil in all cases.

TABLE 3

Numbers of microorganisms in artificial rhizosphere and in control soil

	MOISTURE CONTENT*	FUNGI†		ACTINOMYCETES	
		Number	$\frac{R}{S}$ ratio‡	Number	$\frac{R}{S}$ ratio
	per cent				
Solution after Bison..........{	60	127.5	3.1	7.3	1.6
	30	225.4	8.1	5.3	1.3
Solution after Novelty........{	60	242.4	5.9	5.8	1.3
	30	300.6	10.9	4.5	1.1
Original solution..............{	60	126.5	3.1	14.0	3.1
	30	166.2	5.9	11.6	2.8
Distilled water...............{	60	64.5	1.6	6.8	1.5
	30	75.3	2.7	6.2	1.6
Control soil.................{	60	41.3	....	4.5	...
	30	28.0	....	4.2	...

* Percentage of total moisture-holding capacity.

† Fungi in thousands, actinomycetes in millions, per gram moisture-free soil.

‡ $\dfrac{R}{S} = \dfrac{\text{Number of organisms in artificial rhizosphere}}{\text{Number of organisms in control soil}}$.

The moisture content of the soil showed a marked influence on the density of the fungi in the artificial rhizosphere. The rhizosphere of the drier soil (30 per cent) supported a larger fungus population than that of the moist (60 per cent) soil, and showed a rhizosphere-soil ratio about twice that of the latter. In conformity with the results from the natural rhizosphere, the fungus population in the "rhizosphere" created by the solution after growth of Novelty was more dense that that after growth of Bison. Though the trend in the artificial rhizospheres created by the solutions after growth of Bison and Novelty is the same as in corresponding natural rhizospheres, the numbers were greater in the former.

TABLE 4

Incidence of fungi isolated from artificial rhizosphere and from control soil

Numbers of fungi in thousands per gram of moisture-free soil

| FUNGI | SOLUTION AFTER BISON | | | | | | SOLUTION AFTER NOVELTY | | | | | | ORIGINAL SOLUTION | | | | | | DISTILLED H₂O | | | | | | CONTROL SOIL | | | | | |
| | 60 per cent soil moisture | | | 30 per cent soil moisture | | | 60 per cent soil moisture | | | 30 per cent soil moisture | | | 60 per cent soil moisture | | | 30 per cent soil moisture | | | 60 per cent soil moisture | | | 30 per cent soil moisture | | | 60 per cent soil moisture | | | 30 per cent soil moisture | | |
	No. of cultures	No. of fungi	% of total	No. of cultures	No. of fungi	% of total	No. of cultures	No. of fungi	% of total	No. of cultures	No. of fungi	% of total	No. of cultures	No. of fungi	% of total	No. of cultures	No. of fungi	% of total	No. of cultures	No. of fungi	% of total	No. of cultures	No. of fungi	% of total	No. of cultures	No. of fungi	% of total	No. of cultures	No. of fungi	% of total
Mucor	2	8.8	6.9	2	14.5	6.5	1	6.4	2.6	2	16.2	5.4	2	10.1	8.0	1	8.3	5.0	2	6.4	10.0	1	3.8	5.0	1	1.9	4.6			
Rhizopus	1	4.4	3.5				3	19.2	7.9	1	8.1	2.8	2	10.1	8.0	1	8.3	5.0	1	3.2	5.0				1	1.9	4.6			
Alternaria	1	4.4	3.5	1	7.3	3.2	2	12.7	5.3	3	24.4	8.0	1	5.0	4.0										1	1.9	4.6	1	1.5	5.5
Aspergillus	3	13.2	10.4	2	14.5	6.4	2	12.7	5.3	3	24.4	8.1	2	10.1	8.0	3	24.9	15.0	2	6.4	10.0	3	11.2	15.0	2	3.7	9.2	2	3.1	11.1
Cephalosporium	1	4.4	3.4				6	38.3	15.8	3	24.4	8.1	1	5.0	4.0				2	6.5	10.0									
Cladosporium	2	8.8	6.9	3	21.9	9.7	1	6.4	2.6	2	16.2	5.4																		
Cylindrocarpon	1	4.4	3.4				2	12.8	5.2	3	24.4	8.1																		
Fusarium	1	4.4	3.4	1	7.3	3.2	4	25.5	10.5	5	40.6	13.5	4	20.2	16.0	3	24.9	15.0	2	6.5	10.0	2	7.6	10.0	3	5.6	13.5	1	1.5	5.6
Helminthosporium	1	4.4	3.4	1	7.3	3.2	2	12.7	5.3	4	32.5	10.8													1	1.9	4.6			
Metarrhizium				1	7.3	3.2	2	12.7	5.3				1	5.1	4.0				1	3.2	5.0				1	1.9	4.6			
Penicillium	8	35.2	27.6	10	72.7	32.3	6	38.3	15.8	5	40.6	13.5	6	30.4	24.0	7	58.2	35.0	6	19.4	30.0	8	30.1	40.0	7	13.3	31.5	9	14.2	50.0
Stachybotrys	1	4.4	3.5							3	24.4	8.1	1	5.1	4.0				1	6.5	10.0	1	3.8	5.0	1	1.9	4.6	1	1.5	5.6
Trichoderma	4	17.5	13.7	6	43.6	19.4	2	12.7	5.3	2	16.2	5.4	2	10.1	8.0	3	25.0	15.0				1	7.5	10.0	2	3.7	9.1	3	4.7	16.6
Verticillium	1	4.4	3.5				3	19.2	7.9	1	8.1	2.8	1	5.1	4.0	1	8.3	5.0				1	3.8	5.0	2	3.7	9.1	1	1.5	5.6
Undetermined	2	8.8	6.9	4	29.0	12.9	1	6.4	2.6				2	10.2	8.0	1	8.3	5.0	1	3.2	5.0	2	7.5	10.0						
Total..........	29	127.5	100	31	225.4	100	38	242.4	100	37	300.5	100	25	126.5	100	20	166.2	100	20	64.5	100	20	75.3	100	22	41.4	100	18	28.0	100

The data also indicate that the actinomycetes responded beneficially to the original Crone's solution. In general, however, the density did not differ much between the different treatments.

Qualitative

The qualitative study of the fungus population in the artificial rhizospheres and the frequency of isolates of each genus are summarized in table 4. Fourteen genera were identified. The data also indicate that different genera responded differently to each treatment. *Penicillium, Fusarium, Trichoderma,* and *Aspergillus* were predominant in all samples studied.

The picture of generic frequency and of the percentage of total fungus population in each treatment is approximately the same as in natural rhizospheres. *Fusarium,* for example, in the artificial rhizosphere in the moist soil comprised, in the case of Bison 3.4 per cent, in Novelty 10.5 per cent, in the original solution 16 per cent, in distilled water 10 per cent, and in the control soil 13.5 per cent of the total fungus population respectively. The density of *Fusarium, Helminthosporium, Cephalosporium, Alternaria,* and *Verticillium* was accelerated to a greater extent by the solution after growth of Novelty than by that after Bison, showing a similar picture to that of the natural rhizosphere. The results of this experiment indicate that by-products of growth of Bison and of Novelty influence the activity of soil microorganisms differently.

FACTOR CONTROLLING THE ACTIVITY OF CERTAIN FUNGI

To investigate further the differences between the by-products of growth of the flax varieties in question, a series of agar (1 per cent) media from the solutions described were prepared with the addition of 0.00, 0.01, and 0.05 per cent dextrose respectively. Concentrated agar and destrose solutions were sterilized separately (dextrose in flowing steam) and cooled to 42°C., and the volumes required to make the desired concentrations of media were mixed with solutions after plant growth and poured into Petri dishes. After hardening, the media were inoculated with the following fungi: *Fusarium culmorum, Helminthosporium sativum,* and *Trichoderma viride.* The rate of growth was recorded daily by measuring the diameter of each colony. The average growth of each colony as influenced by the by-products of growth of resistant and of susceptible varieties is summarized in table 5. The results indicate that growth of *Fusarium* and *Helminthosporium* was more abundant on media prepared from solutions after growth of Novelty (figs. 8, 9, 10, 12) whereas that of *Trichoderma* (fig. 11) was better on media from Bison. The addition of dextrose produced better growth in all cases, but the relative growth on the different media remained the same.

To check this experiment, 50 ml. of each solution was dispensed into sterile 250-ml. Erlenmeyer flasks, and sufficient dextrose solution was added to correspond with the concentration of the agar media. Each series of solutions was inoculated with equal volumes of spore suspension of the aforementioned

fungi. After 9 days' incubation at 28°C., the mycelium from individual flasks was filtered on paper of known weight, rinsed several times with distilled water, allowed to dry in the oven overnight at 65°C. and for 2 hours at 100°C., cooled, and weighed. The average weights of duplicate tests of each treatment are summarized in table 6. From the data it is apparent that the solution after growth of Novelty produced a higher yield of *Fusarium* and *Helminthosporium* than the solution after growth of Bison. *Trichoderma*, on the other hand, gave a higher yield in the solution after growth of Bison. The addition of dextrose to the solutions resulted in increased weight of mycelium in all cases and accentuated the difference between the treatments.

It has been shown by Reynolds·(9) that the degree of resistance in flax varieties to *Fusarium lini* is directly correlated with the amount of hydrocyanic acid recovered from plant tissues. The results of this experiment

TABLE 5

Rates of growth of fungus colonies as influenced by by-products of plant growth

FUNGUS	DEXTROSE ADDED	SOLUTION AFTER BISON	SOLUTION AFTER NOVELTY	CONTROL—ORIGINAL SOLUTION
	per cent			
Fusarium....................	0.00	+	++	+
	0.01	++	+++	++
	0.05	+++	++++	+++
Helminthosporium.............	0.00	+	++	+
	0.01	++	+++	++
	0.05	+++	++++	+++
Trichoderma.................	0.00	++	+	+
	0.01	+++	++	++
	0.05	++++	+++	+++

Note: + = poor growth, ++ = moderate, +++ = good, ++++ = very good.

suggest the possibility that the resistant variety excreted or diffused through the root system into the surrounding medium a cyanogenetic glucoside or the product of its hydrolysis, hydrocyanic acid.

To test for the presence of hydrocyanic acid the solutions were titrated with 0.01 M AgNO$_3$ with the addition of a few drops of 5 per cent KI, as described by Bishop (4). It was found that solutions in which the resistant variety was grown contained from 25.3 to 37.6 mgm. HCN per plant, whereas the solution after growth of the susceptible variety contained only a trace. The solutions were kept overnight in the incubator at 28°C. and then distilled by the method outlined by Bishop. The figures thus obtained are somewhat lower than those by straight titration, namely 23.8 and 35.0 mgm. respectively, and only a trace in the solution after growth of Novelty.

To study the influence of KCN on the activity of fungi, series of media

were prepared as follows: Crone's nutrient solution was used as a basal medium, 50 ml. of which was poured into each of a series of 250-ml. Erlenmeyer flasks and autoclaved for 20 minutes at 15 pounds' pressure. A concentrated solution of KCN was prepared with distilled autoclaved water, so that each 5 ml. of solution contained 4.1 mgm. KCN, which when added to the 50 ml.

TABLE 6

Growth of fungi as influenced by by-products of plant growth

MEDIUM	DEX-TROSE ADDED	FUSARIUM			HELMINTHOSPORIUM			TRICHODERMA		
		mgm.	per cent	Ratio*	mgm.	per cent	Ratio*	mgm.	per cent	Ratio*
	per cent									
Control (original solution)	0.00	5	100	100	3	100	100	6	100	100
	0.01	..	...	...	..	...	...	..	...	...
	0.05	10	200	100	8	267	100	9	150	100
Solution after growth of Bison	0.00	1	20	20	3	100	100	10	167	167
	0.01	11	220	...	10	333	...	12	200	...
	0.05	11	220	110	7	233	88	46	767	511
Solution after growth of Novelty	0.00	14	280	280	11	367	367	11	183	183
	0.01	13	260	...	12	400	...	11	183	...
	0.05	16	320	160	19	633	238	18	300	200

* Ratio of corresponding concentration of dextrose.

TABLE 7

Growth of fungi as influenced by KCN

MEDIUM	DEX-TROSE ADDED	FUSARIUM			HELMINTHOSPORIUM			TRICHODERMA		
		mgm.	per cent	Ratio*	mgm.	per cent	Ratio*	mgm.	per cent	Ratio*
	per cent									
Basal.............	0.00	4	100	100	5	100	100	7	100	100
	0.01	6	150	100	9	180	100	9	128	100
	0.05	11	275	100	12	240	100	11	157	100
Basal + KCN......	0.00	3	75	75	4	80	80	9	128	128
	0.01	5	125	83	6	120	67	14	200	156
	0.05	8	200	73	7	140	58	18	257	164

* Ratio of corresponding concentrations of dextrose.

of basal medium made the concentration approximately equal to that obtained after growth of the resistant variety. To some of the series of media thus prepared a concentrated sterile solution of dextrose was added to bring its content to 0.01 and 0.05 per cent. The flasks were then inoculated with an equal volume of spore suspension of the same fungi. The time of incuba-

tion and the procedure of recovering and drying of mycelium were the same as already described. The results of this experiment are summarized in table 7. From the data it is apparent that addition of 4.1 mgm. of KCN to the 50 ml. of basal medium depressed the growth of *Fusarium* and *Helmintho-sporium* as compared with the yields on the basal medium without KCN. *Trichoderma*, however, was stimulated by the addition of KCN. The results of this experiment once again illustrate the similarity of the trend of growth of fungi with the results previously obtained, and support the findings that the resistant variety excretes or diffuses hydrocyanic acid through the root system into the surrounding medium.

DISCUSSION

In general it is accepted (15) that the greater microbial accumulations in the vicinity of the roots (rhizosphere) of growing plants than elsewhere in the same soil are due to the modification of the chemical composition and the structure of that part of the soil. The changes are ascribed chiefly to: (*a*) the deposition of the epithelial cells of the growing roots and the dead parts of the roots; (*b*) excretion by the roots of readily assimilable organic substances; (*c*) excretion of organic acids and CO_2 which change the reaction of the soil solution and the solubility of certain soil constituents; (*d*) modification of the structure of the soil, thus making it a more favorable medium.

Some workers emphasize particularly the importance of the root excretions as a source of food and energy for activity of soil microorganisms. Thus, Kostychev (6) says, "It is impossible to assume that such enormous numbers of living things in the rhizosphere are dependent upon humus and remains of dead roots (mainly cellulose) as a source of food and energy. The experiments indicated that under natural conditions the matter mentioned decomposed extremely slowly; the speed of decomposition does not correlate even approximately with the quantity of CO_2 produced by microorganisms." Starkey (10) similarly suggested, "The extent of the effects of plants upon the soil organisms is not determined by the size of the different plants or the extent of root development but may be associated with some characteristics of the physiology of the plants, particularly as regards quality and quantity of root excretions." Results obtained in this laboratory (17) indicate that both flax varieties, when grown under aseptic conditions, excrete significant amounts of thiamin and biotin substances which may explain the enormous accumulation of microorganisms in the rhizosphere of growing plants. It does not, however, explain the difference in microbial density in the rhizosphere of susceptible and resistant varieties.

Reynolds (9), working on the problem of resistance of flax varieties to *Fusarium* wilt, reported that degree of resistance in flax varieties is dependent upon the amount of the glucoside, linamarin, present in the plant tissues. The evidence presented in this investigation indicates that a significant quantity of the by-product of hydrolysis of linamarin, namely HCN, is excreted or diffused through the root system by the resistant variety, when grown under

aseptic conditions, whereas the susceptible variety excreted only a trace. Furthermore, from a comparison of the density of microbial accumulations in the rhizospheres of susceptible and resistant varieties it can be assumed that the same toxic matter is excreted by the resistant variety under natural (field) conditions, creating unfavorable conditions for the growth of not only the pathogenic organisms but also of certain groups of authochtonous flora of the soil.

It has also been demonstrated in this investigation that different fungi respond differently to minute quantities of HCN, and since the resistant variety excretes HCN into the surrounding medium it exercises selective power upon the fungus flora of the rhizosphere. *Trichoderma viride* deserves special attention because it is not only able to tolerate small quantities of hydrocyanic acid better than certain pathogenic fungi (*Fusarium*, *Helmintho-sporium*) but is also regarded by many investigators (2, 3, 5, 16) as a factor controlling the activity of pathogenic fungi in the soil.

SUMMARY

Comparative studies of the rhizosphere of resistant and susceptible varieties of flax showed that the incidence of *Alternaria*, *Cephalosporium*, *Fusarium*, *Helminthosporium*, and *Verticillium* was relatively lowered and that of *Mucor*, *Cladosporium*, *Penicillium*, and *Trichoderma* increased by the "rhizosphere effect" of the resistant variety as compared with the susceptible variety or control soil. The difference was more apparent in the samples obtained from the drier soil (30 per cent of total moisture-holding capacity).

Methods for growing plants under aseptic conditions and the technique of preparation of collodion membranes are fully described. It was found that when the solutions in which plants had been grown were allowed to diffuse through the collodion membranes into the soil, the microbial activities in the vicinity of the membrane were stimulated in a manner analogous to that in the natural rhizosphere of corresponding plants. The solution after growth of the susceptible variety, when added to liquid or solid media, induced a greater stimulation of growth of *Fusarium* and *Helminthosporium* than the solution after growth of the resistant variety. In the case of *Trichoderma*, however, the solution after growth of the resistant variety exerted greater stimulation. Chemical analyses indicated that the solutions after growth of the resistant variety contained from 25 to 37 mgm. HCN per plant grown, whereas the solution after growth of the susceptible variety contained only a trace. KCN when added to Crone's solution (8.2 mgm. per 100 ml.) exerted an effect on the growth of the same fungi analogous to that produced by the solution after growth of the resistant variety.

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PLATE 1

FIG. 1. Left: arrangement of glass rods and aeration tube; Right: glass rods covered with second layer of cotton.

FIG. 2. Left: size of glass rod; Right: glass tube, lower end plugged with rubber stopper and upper with cotton plug; center: plant growing through the glass tube.

FIG. 3. Plants growing in aseptic culture.

FIG. 4. Permeometer; rate of diffusion measured directly on the 1-ml. graduated pipette.

M. I. TIMONIN
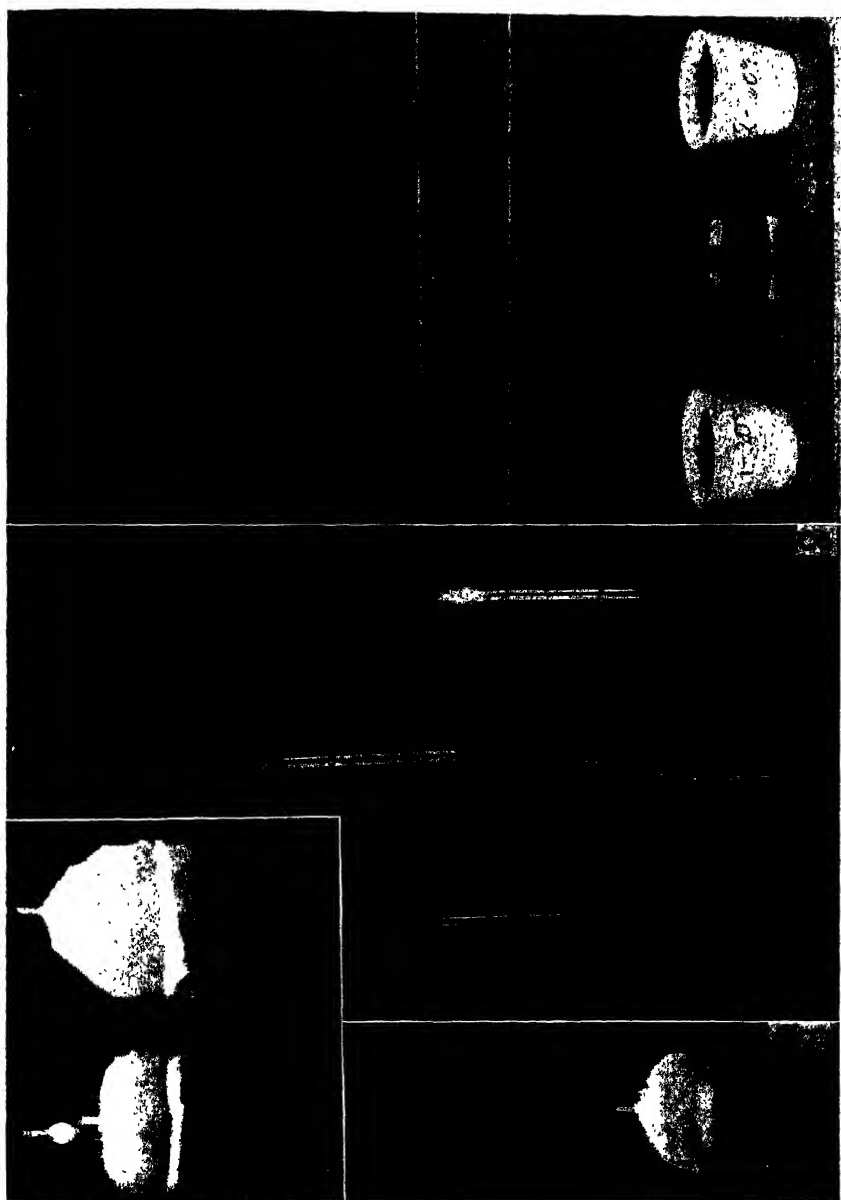
FIGS. 1–4

PLATE 2

GROWTH OF HELMINTHOSPORIUM ON THE MEDIA PREPARED WITH SOLUTION AFTER GROWTH OF FLAX VARIETIES

FIGS. 5, 6, 7. Media prepared with solution after growth of Bison with addition of 0.00, 0.01, and 0.05 per cent of dextrose respectively (75×).

FIGS. 8, 9, 10. Media prepared with solution after growth of Novelty with addition of 0.00, 0.01, and 0.05 per cent dextrose respectively (75×).

FIGS. 5–10

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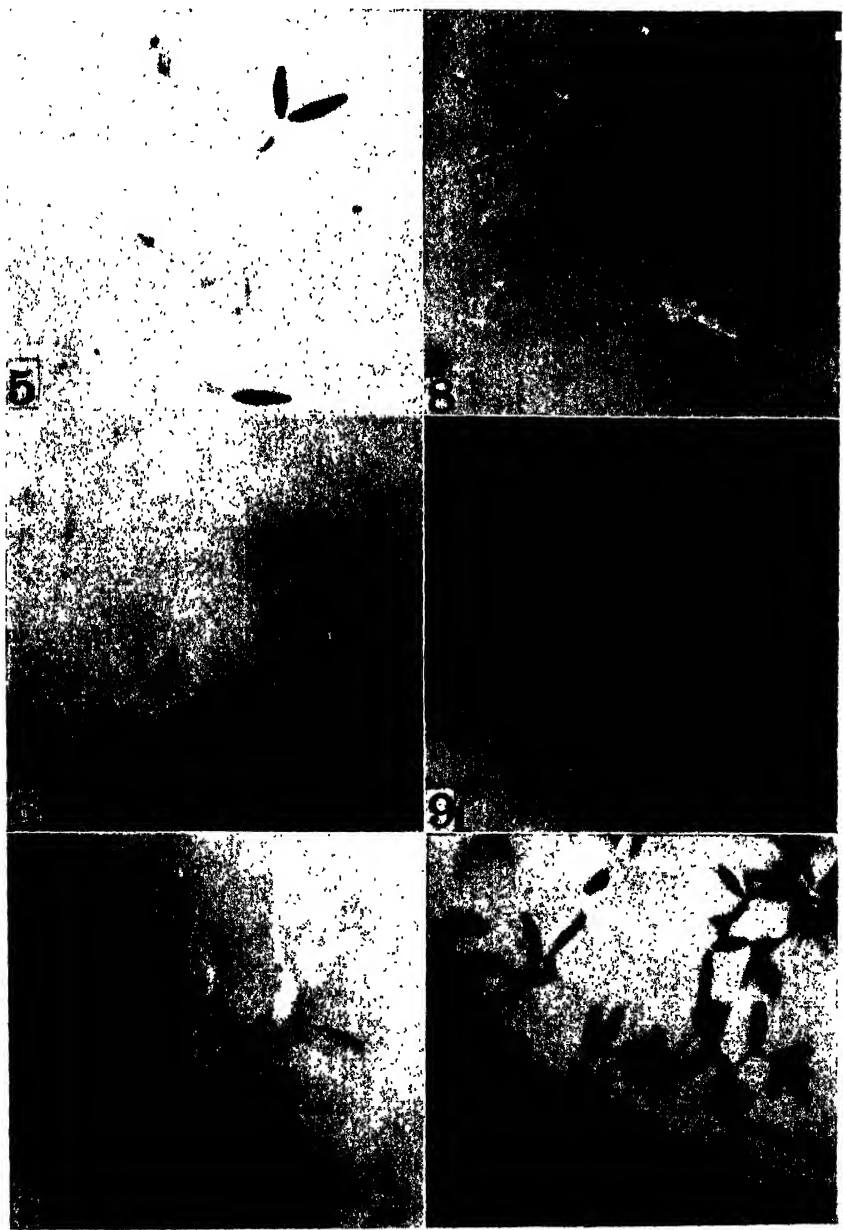
PLATE 3

FIG. 11. Growth of *Trichoderma* as influenced by by-products of growth of flax varieties, media prepared with: left to right, original solution, after growth of Novelty, and after growth of Bison.   Upper row: 0.5 per cent dextrose added, lower row: without dextrose.

FIG. 12. Growth of *Fusarium* as influenced by by-products of growth of flax varieties; media prepared with: left to right, original solution, solution after growth of Bison, solution after growth of Novelty.   Upper row 0.05 per cent dextrose added, lower row without dextrose.
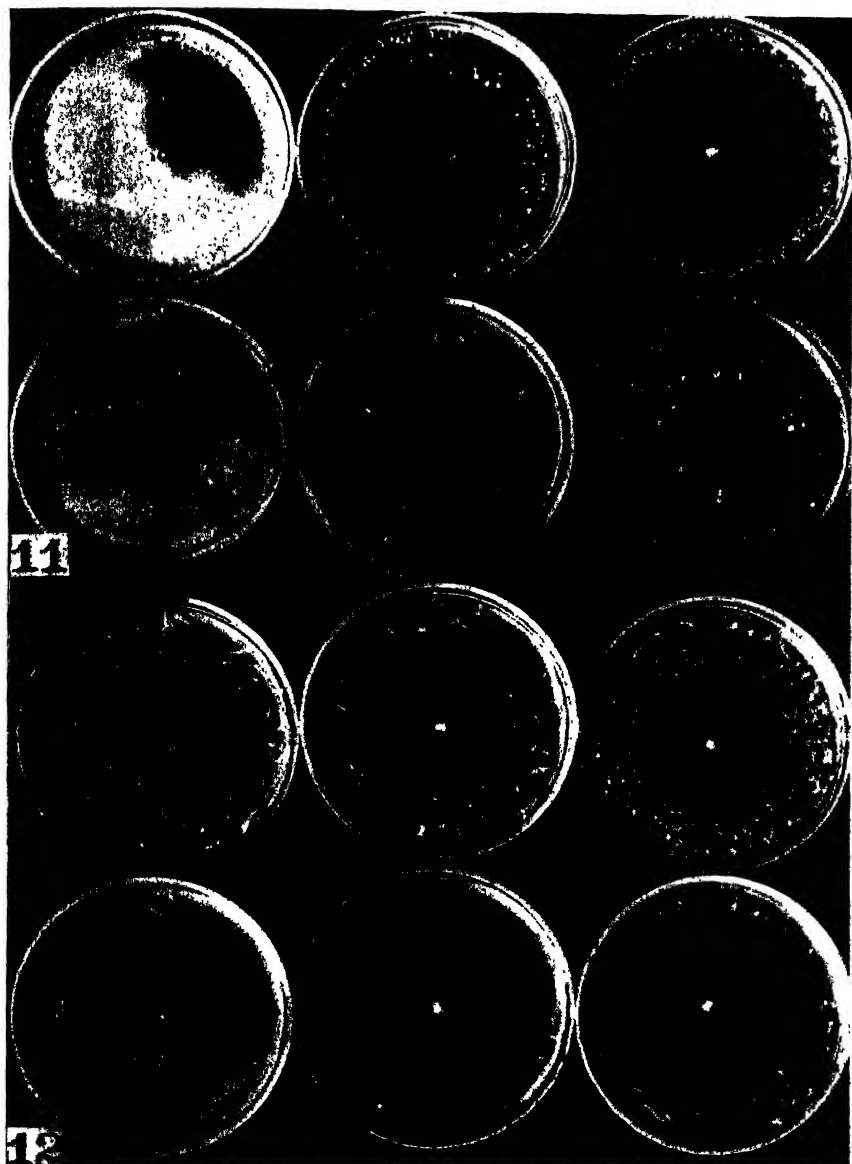
Figs. 11-12

Commercial Fertilizers. Third Edition. By GILBEART H. COLLINGS. The Blakiston Company, Philadelphia, 1941. Pp. 480, figs. 131. Price, $4.50.

Rapid expansion of knowledge concerning soil and plant relationships and advances in methods of manufacturing fertilizer materials and mixtures have made it necessary for the author to modify former statements, introduce new paragraphs, and write a few additional chapters. One new feature is the chapter on ammonia solutions. Nutrient deficiency symptoms are shown in natural colors. This volume is a good presentation of the problems involved in the manufacture and use of fertilizers.

Factors of Soil Formation. By HANS JENNY. McGraw-Hill Book Company, Inc., New York, 1941. Pp. 281, figs. 125. Price, $3.50.

An advanced treatise on theoretical soil science in which time, parent material, topography, climate, and organisms are considered as soil-forming factors. The methods of chemistry and physics are applied to soil data in an attempt to formulate quantitative laws that permit of mathematical treatment. A unique approach to the study of an old problem.

Practical Methods in Biochemistry. Third Edition, revised. By FREDERICK C. KOCH. The Williams & Wilkins Company, Baltimore, 1941. Pp. 314, figs. 17. Price, $2.25.

A laboratory manual intended primarily for the use of medical students, but of interest to all workers in the field of plant and animal chemistry. It deals with both qualitative and quantitative methods of examination of cell constituents, of the secretion of the digestive tracts, and of blood and urine. A very useful book for ready reference on methods employed in this highly important field of chemistry.

The Soils That Support Us. By CHARLES E. KELLOGG. The MacMillan Company, 1941. Pp. 370, figs. 80. Price, $3.50.

"This book is about soil, and how soil and peoples get on together," according to the introductory sentence in the preface. Its purpose is to present the principles of soil science in nontechnical language for the benefit of those who are not specialists in this field but are interested in it and seek to know more about the land on which we live. Some of the chapter headings are interesting in themselves, as, for example, Life and the Soil; The Rains Come and Go; Soils of the Desert; Men Use the Soil; Plowing and Digging; When Do Soils Wear Out; and Soil and Our Future. The illustrations are especially

well chosen. Both the technician and the lay reader will find this book of interest and of value in understanding what the soil is and what its conservation means in terms of national welfare.

Vegetable Growing. Third Edition. By JAMES EDWARD KNOTT. Lea and Febiger, New York, 1941. Pp. 356, illus. 80. Price, $3.25.

All the important vegetables from artichokes to yams are included in this handy volume, which is designed to tell the reader what to do in growing them and how to do it. Reasons for the methods employed and explanations for the plant responses obtained are given wherever feasible. A ready reference book for all those who have to do with the growing of these crops.

THE EDITORS

WIND EROSION OF SOIL IN RELATION TO ROUGHNESS OF SURFACE[1]

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Studies conducted by Bagnold (1, 2) showed that the rate of sand flow q under any wind force may be expressed by $q = C \sqrt{\dfrac{d}{D}\dfrac{\rho}{g}}\, V@^3$ in which C is a constant varying from 1.5 for sand of nearly uniform size to 2.8 for that of a wide range of size, d is the average diameter of grain carried, D is 0.025, ρ the density of air, g the gravity constant and $V@$ is the so-called "friction velocity" in the logarithmic law and determines the slope of the velocity distribution curve when the velocity is plotted against the logarithm of height. $V@$ is equal to $\dfrac{Vz - Vt}{5.75 \log \dfrac{z}{k'}}$, in which Vz is the velocity at any height z, and Vt is the velocity at height k', which is equal to about the height of surface ripples produced by drifting sand. For constant sand conditions all velocity distribution curves converge to one definite Vt value.

Bagnold's formula shows that there is a definite relation between the rate of sand flow and the height of surface ripples, as indicated by the value of k'.

The data presented in an earlier paper (4) showed that the moving soil particles over any type of dune material influenced the velocity distribution curve in the same way as the eroding sand studied by Bagnold. It was further shown that the rate of soil flow q over freshly formed soil and sand dunes, with some exceptions, varied approximately as $V@^3$. Over ordinary cultivated soils in a wind tunnel, however, the rate of flow was never constant but diminished with duration of exposure, ceasing after the surface became stabilized with particles too coarse to be moved by the wind.

The object of this paper is to present further information on the influence of roughness of surface on the intensity of drifting of (a) dune materials, over which the rate of flow remains constant under constant wind velocity, and (b) cultivated soils, the rate of flow over which is not constant but varies markedly with duration of exposure.

The laboratory and the portable field tunnels used in this study were described in earlier papers (3, 4). The area of the exposed soil in the laboratory tunnel was 12 feet long and 20 inches wide and that in the portable tunnel 40 feet long and 4 feet wide.

The effects of two degrees of roughness were compared—of ridges 2.5 inches from bottom of furrow to top of crest and 9 inches wide, running at right angles to the wind, and of a smooth surface. The surface over dune material was leveled with a straightedge, but cultivated soils containing lumps up to 1.5 inches in diameter were merely leveled off with the palm of the hand, the maximum height of clod obstruction being about 0.75 inch. The dune materials used were dry soil or sand freshly deposited by wind against various obstructions.

The intensity of drifting over dune materials was measured by the rate of flow, and that over cultivated soils containing mixtures of erosible and non-erosible fractions, by both the rate of flow and the amount removed up to the time when no further drifting took place. The amount of soil removed was measured by the difference in the weight of the thoroughly air-dry soil before and after exposure. The amount of soil removed divided by the length of the exposure interval gave the rate of flow presumably as at the time midway between the beginning and the end of the exposure interval. The minimum interval of time for which an accurate determination could be made was 30 seconds.

Wind velocities at different heights were determined by a set of six Pitot tubes and a multiple alcohol manometer. For measuring velocities very close to the surface of the ground and between soil ridges, where even a backward wind direction was encountered, a very slender Pitot tube of a total length of only 2 inches was used. It was mounted in such a way as to be easily adjusted to face almost any vertical or horizontal direction. Single velocity readings were always taken at a 12-inch height, measured as from a perfectly leveled surface. The amount of lowering of the soil surface during exposure to the wind was also determined and, where necessary, corrections due to changes in height of readings were made.

The relative degree of wind eddying, as affected by roughness of surface, was measured by small pressure plates as designed by Schmidt (6). These plates oscillated with even a slight pressure of the wind and, having a small period of oscillation, they could reproduce rapid changes in air motion. A set of eight plates mounted on a wire frame 1 foot square was used. The degree of eddying was determined by the relative amplitude of plate oscillation, as indicated by photographs obtained with 10-second exposures. Stiff, thread-like appendages attached to the bottom of each plate facilitated the determination of the degree of oscillation.

All determinations were replicated two to nine times, depending on the type of experiment and the consistency of the results obtained.

INFLUENCE OF ROUGHNESS OF SURFACE OVER VARIOUS DUNE MATERIALS

The results obtained on three types of dune material, including clean dune sand, were analyzed, with special reference to the relations of wind velocity distribution, surface roughness, and the rate of soil or sand removal by wind. The data given in table 1 show the height and wave length of ripples produced by wind and their relation to the value of k'.

TABLE 1

Relation between wind velocity distribution and surface roughness of dune materials

AVERAGE GRAIN DIAMETER	$V@$	Vt	k'	RIPPLES	
				Height*	Wave length
cm.		cm./sec.	cm.	cm.	cm.
Dune material from fine sandy loam (in field tunnel)					
0.011	49.8	179	0.20	0.4	20.3
0.011	71.5	179	0.20	0.5	22.9
0.011	84.0	179	0.20	1.0	25.4
0.011	103.5	179	0.20	1.0	†
Erosible sand and clay material (in field tunnel)					
0.034	40.6	300	0.35	0.3	20.3
0.034	58.7	300	0.35	0.5	25.4
0.034	83.3	300	0.35	0.6	30.5
0.034	101.0	300	0.35	0.8	†
Clean dune sand (in field tunnel)					
0.022	44.8	318	0.30	0.5	19.0
0.022	76.4	318	0.30	0.8	36.0
0.022	93.4	318	0.30	1.1	†
Fine dune clay <0.42 mm. (in laboratory tunnel)					
0.016	48.8	179	0.09	0.4	20.3
0.016	69.4	179	0.09	0.7	25.4
0.016	93.9	179	0.09	1.2	†
Clean dune sand (in laboratory tunnel)					
0.022	67.3	170	0.28	0.2	14.2
0.022	93.4	170	0.28	0.3	22.8
0.022	131.2	170	0.28	...	....

* The height of the top of the ripple above the mean height of the surface.
† Very irregular in wave length.

Bagnold found that the value of k' over a drifting sand surface was approximately equal to the height of the surface ripples produced by wind. The data presented in this paper, on the other hand, show the value of k' to be, on the whole, somewhat lower than the actual height of ripples. It will also

be observed that the height and wave length of ripples did not remain the same but increased with wind velocity, although k' remained constant. The increased height of ripples, however, should have increased the value of k', but their increased wave length apparently counterbalanced this tendency, and therefore the net effect remained the same. It seems that not only the height of the surface roughness but also its lateral frequency affects the rate of flow. The greater the height, the greater is the value of k' and the lower is the rate of flow, but an increase or a decrease in distance between surface obstructions above or below a certain crucial distance appears to lower the value of k', thus increasing the rate of soil flow.
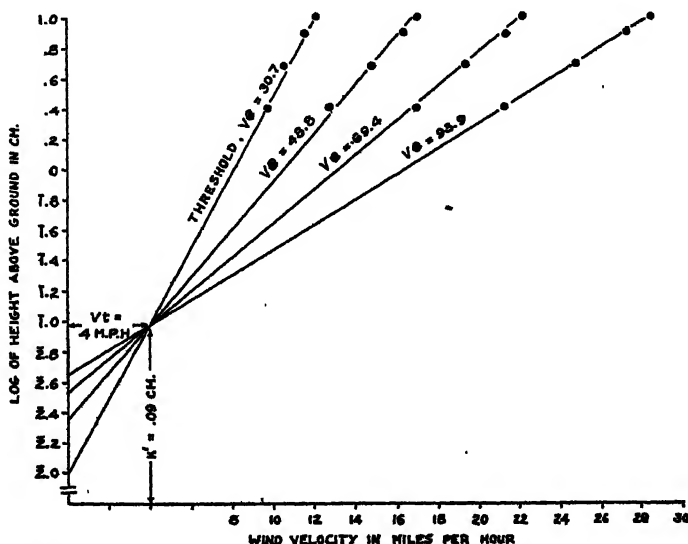
FIG. 1. VELOCITY DISTRIBUTIONS AT DIFFERENT HEIGHTS ABOVE AN ERODING SURFACE OF FINE CLAY DUNE MATERIAL

The surface was smooth at the beginning of each exposure

Immediately on exposure to a wind strong enough to start the movement of soil particles, the smooth surface began to assume a rippled condition, the rate of formation, size, and wave length of ripples increasing with increased wind velocity. Artificial ridges at right angles to the wind, on the other hand, tended to complete obliteration, their rate of leveling off varying directly with wind velocity. The velocity distributions shown in figures 1 and 2 represent averages over the two initially different surfaces for periods of approximately 3 minutes after the beginning of exposure; figure 3 indicates the rate of soil flow for nearly 5 minutes after the beginning of exposure.

Over an initially smooth surface (fig. 1), all projected velocity distribution curves converged to one point k', which in this case was equal to 0.09 cm. At

this height the wind velocity remained constant under any wind force above that required to cause movement of soil particles, irrespective of some changes in the height and wave length of the surface ripples.

The velocity distribution curve represented by $V@ = 47.1$ over the initially ridged surface (fig. 2) denotes the threshold velocity, that is, the minimum velocity required to initiate and continue the movement of soil particles. The size of the ridges after exposure to this wind velocity for 5 minutes remained virtually unaltered, i.e., 2.5 inches high and 9 inches wide as at the beginning of exposure, whereas under that denoted by $V@ = 97.1$ they became completely obliterated in 3.5 minutes, and under $V@ = 94.7$, in 2 minutes. The velocity distribution curves denoted by $V@ = 48.8$, 69.4, and 93.9 over the
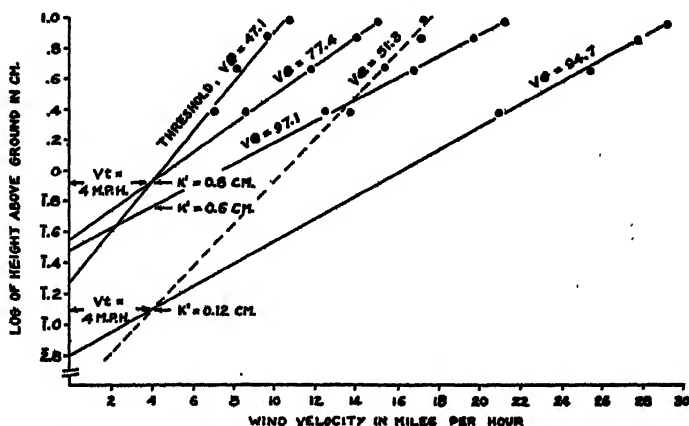
Fig. 2. Average Wind Velocity Distributions Over an Eroding Fine Clay Dune Material Which, at the Beginning of Each Exposure, Was Covered with Ridges 2.5 Inches High, 9 Inches Wide, Running at Right Angles to the Wind

Each curve represents the average velocity during an interval of 3 minutes, at the end of which, the reduction in height of the ridges was proportionate to wind velocity.

initially smooth surface and by $V@ = 77.4$, 97.1, and 94.7 over the initially ridged surface were obtained by the same respective speeds of the propeller producing the wind. Wind velocities at a 12-inch height remained equal over both surfaces, namely, 17, 22, and 30 m.p.h.; but from about a 4-inch height downward they differed considerably in most cases, depending on the differences in the average roughness of surface and the speed of the propeller.

The average wind velocity distribution curves over the initially ridged surface during the first 3 minutes of exposure did not converge to any one point, as over the initially smooth surface. If k' varies directly with surface roughness, the lack of convergence of all velocity distribution curves to some single k' value is to be expected. The curves represented by $V@ = 47.1$ and $V@ = 77.4$ (fig. 2) intersect at a point $Vt = 4$ m.p.h., $k' = 0.8$ cm. After

exposure to these winds for a total period of 8 minutes the ridges became re-
duced from 2.5 inches to about 1.5 inches in height, the height being measured
from the bottom of the furrow to the top of the ridge. Had there been no
reduction in the height of the ridges, the value of k', and perhaps also of Vt,
might be appreciably higher. It is of interest to note that Vt is virtually the
same for both surfaces.

Additional sets of wind velocity readings were obtained on different dune
materials immediately following the exposure of the soil to the highest propeller
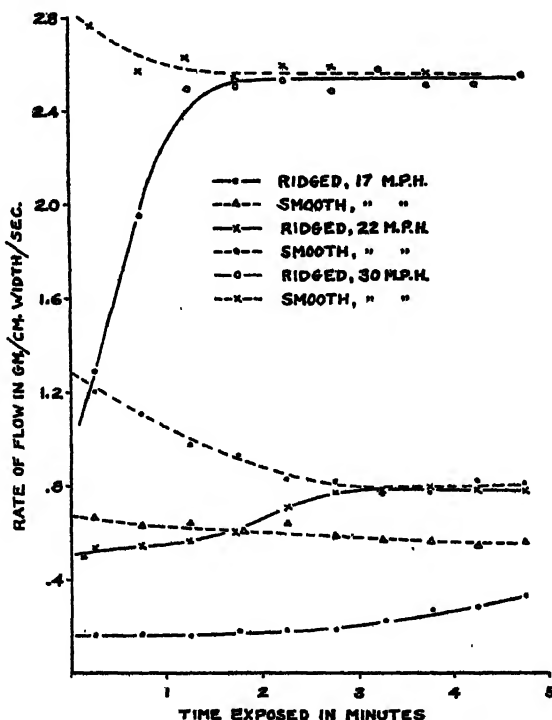
FIG. 3. RATE OF FLOW OF FINE CLAY DUNE MATERIAL OVER THE INITIALLY
RIDGED AND SMOOTH SURFACES UNDER DIFFERENT WIND VELOCITIES

speed. A typical resultant curve so obtained is represented by a broken line
in figure 2. The broken line is found to intersect the continuous line, ob-
tained on exactly the same surface, at $Vt = 4$ m.p.h., $k' = 0.12$ cm. The Vt
and k' values for the intermediate velocity distribution curve represented by
$V@ = 97.1$ could not be obtained on account of the relatively rapid change
in the roughness of the surface. The extreme values of k' were found to be
approximately 0.8 and 0.1 cm., depending on the average roughness of the
surface; that is, the greater the roughness of surface during which the wind
velocity readings were taken, the greater was the value of k'.

The projected velocity distribution curves denoted by $V@ = 93.9$ and 94.7 were approximately the same in slope and vertical position over the initially smooth as over the initially ridged surface. It is evident that under such high velocity as this the effect of ridging this type of soil material is almost nil, the lack of effectiveness being due to very rapid disappearance of ridges.

As shown in figure 3, the initial rate of soil flow was considerably lower over the initially ridged than over the initially smooth surface, irrespective of wind velocity used. Under a 17-m.p.h. wind the rate of flow over the initially ridged surface continued to increase for 5 minutes after the beginning of exposure, at the end of which period the ridges were still about one-half the original height. Under a 22- and a 30-m.p.h. wind the rate of flow increased markedly with duration of exposure until the ridges disappeared completely, after which period both the roughness of the surface and the rate of flow remained constant.

The rate of flow over the initially smooth surface, on the other hand, decreased under all wind velocities used until the ripples formed as a result of the exposure to the wind reached their maximum height. This required close to 5 minutes under a 17-m.p.h. wind, and 3 and 2 minutes under 22 and 30 m.p.h., respectively. The results show conclusive evidence of a marked influence of the roughness of surface on wind erosiveness of soil dunes. It is evident, on the other hand, that ridging this type of soil material is ineffective from the practical standpoint because of the relatively rapid erosion and final disappearance of the ridges.

INFLUENCE OF ROUGHNESS OF SURFACE OVER CULTIVATED SOILS

The intensity of drifting of cultivated soils in a wind tunnel was at first relatively high but decreased rapidly with duration of exposure and ceased as soon as the surface became protected with a bed of aggregates too coarse to be moved by the wind. Typical data in figure 4 indicate that the initial rate of flow over a smooth surface was always markedly greater than under a similar wind velocity over a ridged surface. The data also show a considerable difference in the rate of decrease of flow with time of exposure over the two surfaces. Over the smooth surface the rate of decrease was at all times markedly greater than over the ridged surface. The rate of flow at the beginning of exposure over a smooth surface was two or three times greater than under a similar wind velocity over the ridged surface, but at the end of about 2 minutes' exposure it was about equal. Later it became less and less than over a ridged surface, until finally the movement of soil ceased completely. The time required for movement to cease varied from $\frac{1}{2}$ to 1 hour for a smooth surface and from 1 to $2\frac{1}{2}$ hours for a ridged surface, depending on wind velocity. Table 2 indicates the relative rates of flow over both surfaces on two cultivated soils throughout 40 minutes of exposure to different wind velocities.

The quantity of erosible soil, as measured by the amount of soil removed up to the time when movement ceased, was, under a 17-m.p.h. wind, greater on a ridged than a smooth surface (fig. 5), whereas under a 22-m.p.h. wind it was

about the same or slightly less, and under 30-m.p.h. it was decidedly less. Since, on the whole, more than double the amount of time was required to bring about a complete cessation of erosion over a ridged than over a smooth surface, it is questionable whether the quantity of erosible soil is a fair measure of the relative erosiveness of the two surfaces.
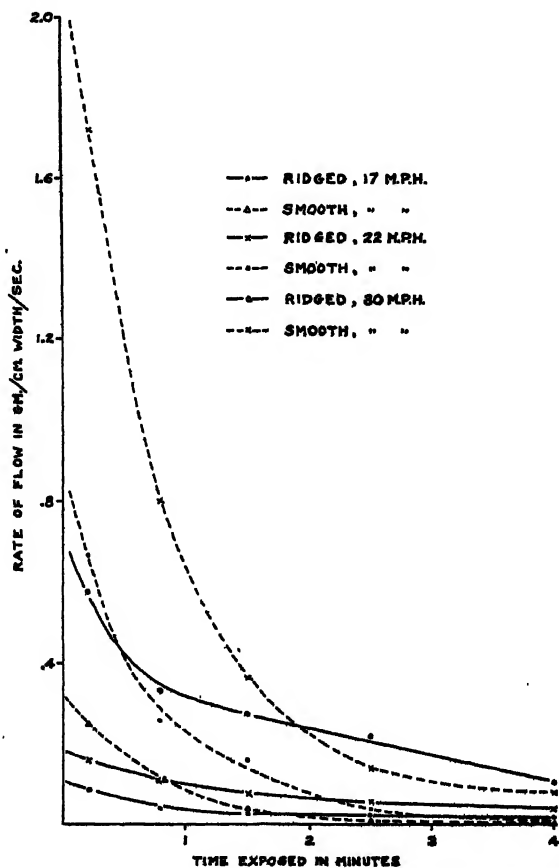
FIG. 4. INITIAL RATE OF SOIL FLOW OVER RIDGED AND SMOOTH SURFACES OF HATTON FINE SANDY LOAM

At cessation of drifting, a quantity of erosible material remained lodged at the leeward sides of the ridges, whereas over a smooth surface most of the erosible soil was blown off. The trapping effect of ridges is apparently an important factor tending to decrease the erosiveness of a ridged surface. This beneficial effect, however, appeared to be counterbalanced to some extent by an increased erosiveness of the soil at the crests of ridges. The crests, protruding as they do into the upper air current, were observed to be con-

siderably more eroded than any part of the smooth surface. On the cultivated soils used, the crests soon became stabilized with coarse, nonerosible fractions, which finally brought about a complete cessation of drifting, but over dry dune materials, such as shown in figure 3, they continued to erode rapidly until the ridges disappeared completely. Plate 1 indicates the typical appearance of a cultivated soil in a ridged and in a smooth condition before and after exposure

TABLE 2

Rate of soil flow, in kilograms per meter width per hour, over smooth and ridged soil surfaces in the laboratory tunnel

MINUTES AFTER START OF EXPOSURE	RATE OF FLOW					
	17-m.p.h. wind		22-m.p.h. wind		30-m.p.h. wind	
	Smooth	Ridged	Smooth	Ridged	Smooth	Ridged
Sceptre heavy clay						
0.25	37.8	25.7	354.0	49.7	811.0	364.0
0.75	17.0	15.0	162.5	36.0	485.0	184.0
1.5	8.3	10.1	63.0	24.8	162.0	102.0
2.5	3.1	7.4	25.9	15.7	68.3	58.0
4.0	1.8	3.7	9.0	10.0	24.0	31.5
7.5	0.8	2.6	2.1	5.0	4.0	16.5
12.5	0.2	1.0	1.0	4.1	2.5	10.0
20.0	0.1	0.5	0.6	2.2	2.6	5.5
30.0	....	0.4	0.3	1.9	2.0	4.2
40.0	....	0.3	0.1	1.3	....	....
Hatton fine sandy loam						
0.25	90.0	29.8	239.8	56.1	618.0	207.0
0.75	40.0	14.3	92.8	38.2	280.8	122.0
1.5	11.2	12.1	56.9	27.8	131.2	98.8
2.5	3.6	9.0	13.0	19.8	51.1	79.1
4.0	1.7	6.6	5.8	14.9	29.6	38.4
7.5	0.9	3.8	3.6	9.2	16.0	20.2
12.5	0.5	1.8	2.0	5.7	6.3	10.7
20.0	0.3	1.1	1.0	3.1	4.7	6.3
30.0	0.2	0.7	0.5	2.3	1.9	4.7
40.0	0.1	0.5	0.3	1.5	1.0	3.3

to the same wind force for the duration required for drifting to cease. Erosion at the crests of ridges, as indicated by the relative degree of exposure of the nonerosible soil clods, is shown to be markedly greater than anywhere over a smooth surface. Deposition of erosible soil on the leeward side of ridges is also indicated, whereas no such deposition could be seen on a smooth surface, except in a limited degree behind some of the larger clods.

The increased erosion at the crests of ridges might be expected to be due to an increase in wind velocity there. A large number of determinations made over

different degrees of roughness of surface, typical results of which were published previously (3), showed a markedly reduced velocity for some distance above a ridged as compared to a smooth surface. Further investigations were conducted with particular reference to wind structure close to and between the ridges. As shown in table 3, there was a definite reduction in wind velocity
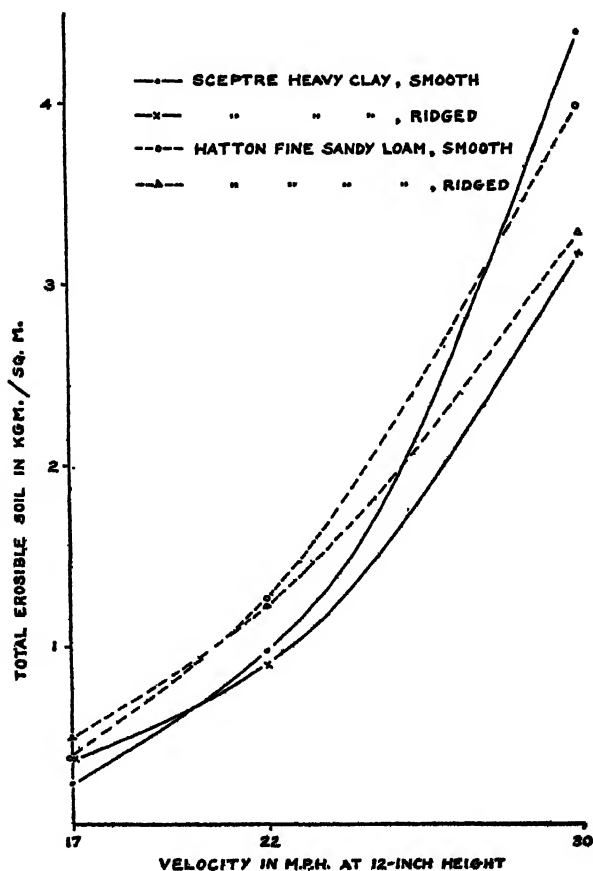
FIG. 5. TOTAL EROSIBLE SOIL ON RIDGED AND SMOOTH SURFACES UNDER DIFFERENT WIND VELOCITIES

at some distance above the ridges, but at 0.06 inch above the crests of ridges the velocity was, on the average, about 1.5 times higher than at a similar height over a smooth surface. The increased surface velocity is apparently the cause of increased erosion at this position.

Between and approximately 1 inch below the crests of ridges, very low velocities, characterized by backward wind direction, were encountered. The structure of wind over ridges is indicated diagrammatically in figure 6, where

TABLE 3

Wind velocities, in miles per hour, over ridged and smooth soil surfaces in the laboratory tunnel

POSITION*	RIDGED				SMOOTH			
	Height above crests of ridges	Propeller speed			Height	Propeller speed		
		1	2	3		1	2	3
	inches				*inches*			
1	0	8.3	10.2	15.7	0.06	5.5	6.9	9.1
2	Below	−3.0	−1.1	−3.3	1	15.2	18.6	25.6
3	Below	−2.7	−2.1	−3.5	2	17.6	21.9	30.0
4	Below	0	−1.9	−6.4	3	19.4	23.5	32.4
5	0	7.2	8.2	11.8	4	19.5	24.6	33.2
6	0.06	8.3	10.3	15.4	6	19.6	24.6	33.2
7	1	12.8	14.9	21.0				
8	2	14.5	17.3	24.9				
9	4	17.6	22.2	31.6				
10	6	19.2	24.3	33.3				

* As designated by number in figure 6. Negative wind velocities denote a backward wind direction.
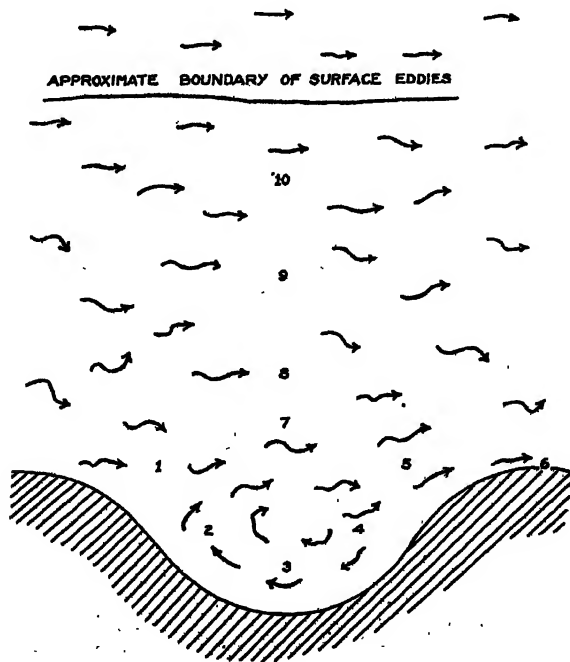
FIG. 6. DIAGRAMMATIC REPRESENTATION OF WIND STRUCTURE ACROSS SOIL RIDGES

Positions 1, 2, 3, 4, and 5 are 1 inch from the soil surface, 1 and 5 being level with the tops of the ridges; 6 is 0.06 inch above the top of the ridge; and 7, 8, 9, and 10 are 1, 2, 4, and 6 inches above and half way between the tops of the ridges.

the directions of the moving air are indicated by arrows. A markedly reduced velocity between the ridges is apparently the cause of soil deposition there. When the velocity between the ridges is disregarded and the velocities above the surface obstructions are expressed by a graph in which the ordinate is the logarithm of the height above an average surface, the curves of velocity become straight lines and conform fairly closely with the generally accepted Prandtl's velocity distribution formula, which shows the relation of the velocity of the wind, the frictional resistance of the surface, and the size of surface obstructions.

A zone of definite eddying, as measured by Schmidt's oscillating plates, extended to about 6 inches above the 2.5-inch ridges. The relative degree of eddying did not appreciably change with wind velocity. Although there was no sharp change between a markedly turbulent surface layer and the upper zone characterized by a more uniform flow, the rate of change was great enough to be easily detected. This observation conforms with that of Durst (5),

TABLE 4

Relative amplitude of Schmidt's oscillating plates over ridged and smooth soil surfaces

HEIGHT ABOVE PEAKS OF SURFACE OBSTRUCTIONS	SMOOTH SURFACE					RIDGED SURFACE				
	1	2	3	4	Average	1	2	3	4	Average
inches										
1	0.85	1.02	1.02	1.12	1.00	2.23	2.23	3.01	3.01	2.62
4	1.03	1.03	1.12	0.93	1.03	0.95	0.98	1.17	1.07	1.04
7	0.90	0.95	0.95	0.81	0.90	0.84	0.66	0.84	0.78	0.78
10	0.80	0.80	0.85	0.80	0.81	0.66	0.66	0.76	0.76	0.71

who first conceived of a probable surface of discontinuity between the frictional eddies caused by air striking against surface obstacles and the less turbulent air above. Durst found that these external frictional eddies extended about 1.5 to 3 times the height of the obstacles.

At 1 inch above the crests of ridges the relative amplitude of oscillation of Schmidt's oscillating plates was about 2.5 times as great as at a similar height above a smooth soil surface (table 4), but at a 4-inch height it was about equal and at a 10-inch height slightly less than over a smooth surface. An increased eddying close to a ridged surface may well be a factor tending to increase the erosion of the soil.

DISCUSSION AND CONCLUSIONS

The lower rate of soil flow over a ridged as compared to a smooth surface seems to be due not only to the sheltering effect of the ridges but also, and more particularly, to their power in reducing the average velocity of the wind for some distance above the average surface of the ground. This reduction in wind velocity would be insignificant if it were not for the fact that much of the

soil is carried in saltation not exceeding 6 inches in height (3). The reduction of the wind's momentum at heights of saltation may be expected to reduce the carrying power of the wind proportionately. But the beneficial effect of ridging appeared to be counterbalanced to a greater or lesser extent by an increased wind force due to increased velocity at the crests of ridges and by greater eddying of the wind. In all cases, however, the apparent decrease in the intensity of erosion caused by the former set of factors greatly exceeded the opposing effects of the latter.

The data in figure 5, showing the amounts of erosible soil on ridged and smooth surfaces, may lead to the formulation of erroneous conclusions, unless something is known of the intensity of soil drifting over the two types of surface. Though it is true that the amounts of erosible soil on the ridged surface of cultivated soils were actually more in some cases than on a smooth surface, the initial intensity of drifting, as measured by the rate of flow, was always less. Over a small area such as that in a wind tunnel, this decreased initial rate of flow may appear to have little or no significance, but over a large field where extremely long periods of time are required to bring about a complete removal of erosible soil, if ever it could be completely removed, it may be of utmost importance. The degree of soil damage, or the degree of injury inflicted upon the growing crop, will be determined not by the quantity of erosible soil found at the surface of the ground but by the rate of soil flow. Hence, the advantage of ridging land becomes apparent—it is to decrease the initial rate of soil flow by which both the amount of soil removed and the extent of injury to growing crops may be reduced.

Though removal of all the erosible soil fractions from a surface of small area, such as in a wind tunnel, is a matter of minutes, removal of such fractions from relatively large fields requires much longer periods. To remove most of the erosible soil fractions from a 12-foot length of the exposed area of moderate surface roughness, at least 30 minutes is required. Assuming that the time required to stabilize the soil varies in direct proportion to the length of the exposed area, at least 5 days of continuous exposure to wind from one direction would be needed to stabilize a half-mile length, a distance encountered over many fields of bare fallow. But erosive winds seldom blow continuously from one direction for such duration as this and usually die down at night, thus prolonging the actual period. A change in wind direction would only prolong the period required to stabilize a given field. Furthermore, appreciable quantities of nonerosible soil in the field are converted to erosible material by the force of abrasion produced by the moving soil particles, whereas over short distances, such as in a wind tunnel, abrasion is virtually eliminated. Even if there were no shift in wind direction or any effect from abrasion of moving soil, the weathering down of the soil surface between erosive days might markedly increase the quantity of erosible soil over and above that already present at the beginning. If the effect of all these factors is taken into account, the

length of time during which the soil is exposed to erosive winds in the field appears to have relatively little effect in reducing the rate of flow, except over relatively small areas. The seriousness of soil drifting seems to be determined to a large extent by the rate of soil flow, which under similar conditions in the tunnel is comparable mainly to the initial rate of flow. Over the same soil surface and under equal wind velocity, the rate of flow and the total quantity of erosible soil vary more or less proportionately, and therefore either type of measurement would indicate the relative erosiveness of a soil; but for two different types of surface the initial rate of flow and the total quantity of erosible soil vary independently of each other.

In conclusion, it may be said that though the quantity of erosible material on cultivated soils under a relatively low wind velocity is somewhat greater over a ridged than over a smooth surface, the initial intensity of drifting, as measured by the rate of soil flow, is always much less over a ridged surface. The initial intensity of drifting seems to be the better indication of the erosiveness of the soil in the field. Ridging cultivated soils reduces the severity of drifting by decreasing the rate of soil flow, but ridging highly erosive dune materials is less effective on account of a relatively rapid disappearance of the ridges.

SUMMARY

The rate of soil flow under a wind force was found to vary inversely with the roughness of the surface which, in Bagnold's formula, is denoted by the relative value of k'. The value of k' appeared to be dependent not only on the height of the surface obstructions but also on their nature and lateral frequency.

Ridging cultivated soils markedly reduced the initial rate of soil flow under all wind velocities used. Factors tending to reduce the rate of soil flow over a ridged as compared to a smooth surface appeared to be the reduction in the average wind velocity for some distance above the average surface and the trapping of soil on the leeward side of ridges. Those tending to increase the rate of flow over ridges appeared to be greater eddying of wind and greater wind velocity and consequent increase of erosion at the crests of ridges. The gross effect of the former pair of factors was always markedly greater than that of the latter.

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PLATE 1

APPEARANCE OF SOIL SURFACES BEFORE AND AFTER EXPOSURE TO A 22-M.P.H. WIND AT A
12-INCH HEIGHT. WIND DIRECTION LEFT TO RIGHT
FIGS. 1 AND 2. Ridged and smooth surfaces before exposure.
FIGS. 3 AND 4. Same after exposure for the length of time required for drifting to cease.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

THE ORGANIC MATTER IN COLLINGTON SANDY LOAM AND IN THE ERODED MATERIAL[1]

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Considerable work has been carried out to determine soil and water losses due to erosion on different soils and under different cultural practices. Little study has been made, however, of the chemical nature of the organic and inorganic fractions of the soil material that has been eroded away, and especially of the amounts of specific soil constituents, such as the organic matter and nitrogen, that are lost as a result of erosion.

Slater and Carleton (4), in an investigation of the soil erosion plots at Clarinda, Iowa, found a correlation between the decrease in organic matter content of the plots and the amount of erosion. Over a period of 6 years a definite decrease in the percentage organic matter occurred each year in plots where erosion was heavy. It was suggested, therefore, that a great deal of the organic matter loss in soils, formerly attributed to decomposition processes, is probably due to erosion.

A study of the microbiological population in the original soil and in the soil runoff showed (7) that the latter contained approximately 200 times as many organisms as the former. This would indicate that the eroded material contained more organic matter than the original soil or that the nature of the organic matter was different in the two.

There is particular lack of analytical data regarding the nature and abundance of organic matter in soil eroded from experimental plots set up specifically to determine soil and water losses. The investigations reported in this paper were carried out in conjunction with the series of Marlboro erosion plots.[2] A study was made of the amount and nature of organic matter in that part of soil which has been eroded away as compared with the organic matter content of the original soil, thus making possible the determination of the organic matter losses due to erosion under a variety of organic matter treatments.

Eight plots designated by numbers 5, 6, 7, 12, 13, 21, 22, and 23 were selected for this study.   They are the largest plots in the Marlboro experiment (14 by 210 feet) and are treated annually as follows:

> Plots   5 and 13—Fertilizer alone.
> Plots   6 and 21—Fertilizer + rye cover crop.
> Plots   7 and 22—Fertilizer + 20 tons stable manure.
> Plots 12 and 23—Fertilizer + 20 tons stable manure + rye cover crop.

All plots are cultivated alike, and the same cultivated crops are grown on all plots.

Aliquot samples of the eroded material removed from the plots by each rain accompanied by soil erosion were taken over a period of $2\frac{1}{2}$ years.   These samples were analyzed for total organic carbon and for total nitrogen.   From these results and from the soil loss data supplied by the workers at the Marlboro station, the total organic matter lost from the various plots was calculated. At suitable intervals, the original soil as well was analyzed for total nitrogen and total carbon.   In order to determine whether the chemical nature of the organic matter removed is comparable to that of the original soil, proximate chemical analyses were made of the organic matter in representative samples of the eroded material and of the original soil.

Methods

Samples of soil were obtained from eight different locations in each plot, equally spaced.   The soil portions were mixed and aliquot samples taken.   The soils were air-dried, passed through a 2-mm. sieve, ground, and dried at 105°C. The analyses were calculated on the oven-dry basis.

The samples of eroded soil were collected and supplied by the personnel of the Marlboro station.   At the station, the eroded material is collected in tanks at the lower end of each plot.   The tanks are so arranged that if the first becomes full during a rainstorm, a known fraction of the overflow is caught in a second tank.   If the second tank becomes full there is a third.   After a storm during which erosion occurs, the material that collects in the tanks is usually allowed to remain for 12 hours.   If a large amount of solid material collects in the first tank, the supernatant liquid is decanted into large containers and mixed well.   Quart samples are taken from the decant.   The sludge, or heavier material left in the bottom of the tank, is mixed well, and pint samples are removed.   If the runoff water contains only a small amount of solid material, the entire contents of the first tank are mixed and quart samples taken.   In all cases quart samples of the material which accumulates in the second or third tank are collected.

When the samples arrived at the laboratory, 1 teaspoonful of a precipitant, a saturated solution of potassium alum, was added to each flask.   The jars were allowed to stand overnight, the clear liquid was siphoned off, the solid

material was washed into beakers, and the contents were evaporated to dry-ness. The eroded material was then sieved, ground, dried at 105°C., and analyzed.

For the proximate analyses, the various samples of soil taken from each plot were mixed, and aliquots were used. For the eroded soil material, the same procedure was followed. All the sludge samples which had been collected from the various plots were mixed, and representative portions were used for analysis. Because the sludge is not fully representative of the total eroded soil, the proximate analyses of this material may not give a true picture of the composition of the total soil lost by erosion. It is believed to be sufficiently representative, however, to throw light upon the nature of the organic matter in the eroded soil as compared with the original soil in the plots.

The total nitrogen determinations were made by the Kjeldahl method and the organic carbon by a modified Schollenberger procedure. The total organic matter was calculated by multiplying the carbon by the factor 1.724 (5). The proximate chemical analyses were carried out according to the method of Waksman and Stevens (6).

Results

Amount of organic matter in original soil and in eroded material. Representa-tive organic matter and nitrogen determinations of the soil in the plots are reported in table 1.

The percentage organic matter and nitrogen in the soil receiving only fertilizer did not change materially during the period covered by the analyses, though there was a tendency toward a slight increase. The average percentages of organic matter and nitrogen of plots 5 and 13 were 1.05 and 0.063 respectively. In plots 6 and 21, the additions of organic matter and nitrogen to the soil in the form of a cover crop were so small and the plant material evidently de-composed so rapidly that no significant increase in the amounts of these two substances over the amounts in the control fertilized plots was evident.

Although no determinations of the percentage of organic matter in the soil of plots 7, 12, 22, and 23 were made before the first manure application in 1938, it appears that additions of manure increased the organic matter and nitrogen content of the soil. Shortly after manure was applied in 1939 and 1940 a definite increase in percentage organic matter and nitrogen was evident. As the manure decomposed there was a gradual decrease. Throughout the period of study the percentage organic matter in the soil receiving manure alone and manure plus cover crop was approximately 0.2 to 0.4 per cent higher than the check plots.

The percentages of organic matter and nitrogen in the soil eroded from the plots as a result of different rains are reported in table 2. Again only data from representative determinations are reported. Although there is a great variation in the values obtained, the eroded material contains a much greater percentage of organic matter and nitrogen than does the soil in the plots. In

most cases the eroded material contained 3 to 8 times as high a concentration of organic matter and nitrogen as the original soil.

An examination of the soil loss data, as obtained by the Marlboro station, together with the data in table 2 reveals that during any particular storm the percentages of organic matter and nitrogen in the material from the plots losing small amounts of soil were generally greater than those in the soil from the

TABLE 1

Organic matter and nitrogen in Collington sandy loam

DATE OF SAMPLING	OCT. 26, 1938*		MAY 11, 1939†		JULY 14, 1939		NOV. 9, 1940		APRIL 24, 1940‡	
Plot	Organic matter	Nitrogen	Organic matter	Nitrogen	Organic matter	Nitrogen	Organic matter	Nitrogen	Organic matter	Nitrogen
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
5	0.93	0.052	0.97	0.057	0.95	0.056	1.09	0.057	1.09	0.063
13	1.00	0.056	1.00	0.069	1.02	0.066	0.98	0.064	1.16	0.063
Ave.........	0.97	0.054	0.98	0.063	0.98	0.061	1.03	0.060	1.12	0.063
6	1.00	0.054	1.05	0.066	1.12	0.066	1.14	0.065	1.24	0.077
21	0.86	0.046	0.91	0.066	0.93	0.063	1.09	0.062	1.14	0.063
Ave.........	0.93	0.050	0.98	0.066	1.02	0.064	1.11	0.063	1.19	0.070
7	1.19	0.064	1.59	0.090	1.60	0.096	1.50	0.090	1.66	0.092
22	1.14	0.052	1.52	0.086	1.47	0.090	1.17	0.072	1.60	0.088
Ave.........	1.16	0.058	1.55	0.088	1.53	0.093	1.33	0.071	1.63	0.090
12	1.10	0.060	1.53	0.083	1.53	0.073	1.41	0.078	1.48	0.083
23	1.14	0.052	1.43	0.073	1.38	0.070	1.31	0.073	1.40	0.080
Ave.........	1.12	0.056	1.48	0.078	1.45	0.071	1.36	0.075	1.44	0.081

* Rye cover crop on plots 6, 21, 12, and 23 planted September 26, 1938.

† Manure on plots 7, 22, 12, and 23 applied April 22, 1939 and cover crop on plots 6, 21, 12, and 23 plowed under March 22 to 29, 1939.

‡ Manure on plots 7, 22, 12, and 23 applied and cover crop on plots 6, 21, 12, and 23 plowed under April 11, 1941.

plots where greater erosion occurred. The great variations in the values obtained for different storms were undoubtedly due largely to differences in rain intensity and in the physical state of the soil at the beginning of the storms. Further information on the hydrologic factors is presented in another paper from this institution.[3]

Organic matter and nitrogen losses. The total organic matter lost from the eight plots from June, 1938, to January 1, 1941 was calculated from the data recorded in table 2. These results are reported in table 3. The losses of

[3] Knoblauch, H. C., and Kolodny, L. To be published.

organic matter depended upon the soil losses; however, the percentage of organic matter in the total eroded material for the entire period was four or five times as high as in the original soil. For example, the average percentage organic matter of the soil in plot 5 was 1.02, whereas that of the organic matter of a composite sample of all the soil eroded from plot 5 was 5 per cent. Consequently the loss of the soil humus was relatively greater than that of the soil. Over the 2½-year period the control plots lost an average of about 1,200 pounds of organic matter per acre as a result of erosion. Since this organic

TABLE 2

Organic matter and nitrogen in soil eroded from Collington sandy loam

DATE OF RUNOFF ...	NOV. 19, 1938		FEB. 29, 1939		JUNE 30, 1939		AUG. 14, 1939		MAY 31, 1940	
Plot	Organic matter	Nitrogen	Organic matter	Nitrogen	Organic matter	Nitrogen	Organic matter	Nitrogen	Organic matter	Nitrogen
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
5	4.23	0.25	7.38	0.37	8.71	0.55	6.13	0.38	6.53	0.38
13	4.67	0.24	5.14	0.22	6.38	0.39	7.03	0.49	5.67	0.31
Ave.............	4.45	0.25	6.26	0.29	7.54	0.47	6.58	0.43	6.10	0.35
6	5.60	0.25	....	....	....	....	6.10	0.37	7.14	0.44
21	3.69	0.18	....	....	....	....	8.10	0.56	5.23	0.28
Ave.............	4.64	0.22	....	....	....	....	7.10	0.46	6.18	0.36
7	4.61	0.23	7.93	0.38	....	....	8.22	0.47	10.60	0.49
22	3.63	0.18	7.39	0.39	....	....	9.37	0.60	10.15	0.51
Ave.............	4.12	0.20	7.66	0.38	....	....	8.79	0.53	10.37	0.50
12	4.81	0.28	....	....	....	....	8.14	0.55	4.96	0.30
23	3.78	0.17	....	....	....	....	5.87	0.35	3.65	0.25
Ave.............	4.29	0.22	....	....	....	....	7.00	0.45	4.30	0.27

matter represents typical soil humus, which is organic matter in an advanced stage of decomposition, and contains large amounts of plant food elements, its removal means the loss of particularly valuable material.

Annual manure applications reduced slightly the losses of humus. An average of 950 pounds per acre was lost from the manured plots during the period reported. A cover crop during the periods when the soil would otherwise be left bare reduced the organic matter losses to approximately half those of the control plots, and the use of a cover crop together with annual applications of stable manure reduced them to a third those of the check plots.

What has been said of the soil organic matter is also true of the soil nitrogen, which is bound up with the humus fraction of the soil.

During the period covered by the analyses, the organic matter applications did not increase the percentage organic matter in the eroded material.

Comparison of organic matter in Collington sandy loam and in eroded soil material. In table 4 are found proximate chemical analyses of the organic matter in the original sandy soil and in the soil lost by erosion.

The humus in the original soil consisted largely of lignin and nitrogenous complexes. Cellulose, hemicelluloses, and alcohol- and ether-soluble sub-

TABLE 3

Organic matter losses due to erosion from Collington sandy loam

YEAR	1938*			1939			1940			TOTAL		
Plot	Soil losses†	Or-ganic matter losses	Or-ganic matter	Soil losses	Or-ganic matter losses	Or-ganic matter	Soil losses	Or-ganic matter losses	Or-ganic matter	Soil losses	Or-ganic matter losses	Or-ganic matter
	lbs./ acre	*lbs./ acre*	*per cent*	*lbs./ acre*	*lbs./ acre*	*per cent*	*lbs./ acre*	*lbs./ acre*	*per cent*	*lbs./ acre*	*lbs./ acre*	*per cent*
5	7,900	345	4.36	8,400	435	5.14	4,100	245	5.92	20,500	1,020	5.00
13	12,000	550	4.58	9,200	480	5.23	6,100	341	5.64	27,300	1,370	4.62
Ave	9,950	447	4.47	8,800	457	5.18	5,100	293	5.78	23,900	1,185	4.81
6	8,200	405	4.92	1,460	79	5.39	1,900	118	6.19	11,600	600	5.19
21	19,900	725	3.64	420	18	4.22	1,760	116	6.55	22,000	860	3.88
Ave	14,050	565	4.28	940	48	4.80	1,830	117	6.37	16,800	730	4.53
7	7,700	380	4.92	9,350	440	4.70	3,000	234	7.69	20,000	1,050	5.23
22	10,000	400	4.01	7,600	318	4.15	2,400	134	5.66	20,000	850	4.26
Ave	8,850	390	4.46	8,475	379	4.42	2,700	184	6.67	20,000	950	4.75
12	5,700	353	6.23	470	26	5.47	1,020	60	5.86	7,170	440	6.12
23	7,700	357	4.61	220	12	5.37	554	26	4.62	8,500	390	4.62
Ave	6,700	355	5.42	345	19	5.42	787	43	5.24	7,835	415	5.37

* Organic matter determinations for 1938 were not complete and therefore figures represent calculated values.

† Soil loss data were supplied by the Marlboro Erosion Experiment Station.

stances were present in very small amounts. The carbon-nitrogen ratio averaged 10.3. It is evident, therefore, that the organic matter in the soil under consideration is in an advanced stage of decomposition.

At the present time it appears that the various plot treatments have not influenced the nature of the soil humus to any great extent. There is, however, a slightly greater percentage of hemicelluloses in the plots receiving organic matter treatments. The organic materials added to the soil apparently decomposed very rapidly.

The eroded soil, represented by the sludge samples which were used for the

proximate analyses, contained approximately three times as much organic matter as the original soil. Inasmuch as the total soil lost from the plots contained approximately five times as great a percentage of organic matter as the original soil, it is evident that the sludge samples do not account for all the organic material washed from the soil. The nature of the organic matter in the eroded soil differed in certain respects from that of the original. The carbon-nitrogen ratio of the eroded soil was lower, the average value for the four treatments being 9.1. As evidenced by the lower carbon-nitrogen ratio, the eroded material contained a greater percentage of organic nitrogenous complexes. Another difference in the nature of the organic matter in the original and eroded soils was in the hemicellulose content; the humus in the

TABLE 4

Proximate chemical composition of organic matter in Collington sandy loam and in eroded material

(Percentage of dry organic matter)

CHEMICAL CONSTITUENTS	ORIGINAL SOIL				ERODED MATERIAL			
	Plots 5 and 13	Plots 6 and 21	Plots 7 and 22	Plots 12 and 23	Plots 5 and 13	Plots 6 and 21	Plots 7 and 22	Plots 12 and 23
Organic matter*.......	1.15	1.18	1.45	1.40	3.39	3.45	3.98	3.47
Nitrogen*.............	0.064	0.070	0.081	0.075	0.218	0.230	0.273	0.200
C/N ratio.............	10.4	9.7	10.3	10.8	9.0	8.7	8.5	10.1
Ether extract..........	1.5	1.4	1.4	1.5	1.3	1.3	1.2	1.9
Alcohol extract........	2.0	2.1	2.2	2.2	1.1	1.2	1.0	1.8
Hemicelluloses.........	2.7	3.6	3.2	4.6	5.5	6.6	5.7	9.0
Cellulose..............	0.5	0.6	0.6	0.7	0.5	1.0	0.8	1.5
Nitrogenous complexes..	34.7	37.0	34.8	33.6	40.1	41.2	42.7	36.1
Lignin humus..........	44.3	44.0	41.5	38.7	43.0	46.7	40.4	45.7
Total constituents accounted for.......	85.7	88.7	83.7	81.3	91.5	98.0	91.8	96.0

* Percentage of dry soil.

eroded material contained approximately twice as much hemicellulose as the humus in the soil itself.

Differences in the nature of the soil humus due to organic matter additions were more evident in the eroded material than in the original soil. The material eroded from the soil into which organic residues had been incorporated contained larger percentages of hemicelluloses and cellulose than the control. The humus washed from the plots receiving the largest organic matter applications also contained a slightly higher percentage of ether- and alcohol-soluble material.

DISCUSSION

The data reported show that large amounts of soil humus may be lost from sandy soil by erosion. As much as nine times as great a percentage of humus was present in the eroded material as in the original soil. Apparently the

bulk of the humus in Collington sandy loam is bound up with the smaller and lighter soil fractions, which are more readily washed from the soil than the heavier sand particles. Consequently the erosion losses are more serious than if the soil as a unit were eroded away.

Organic matter applications did not increase the percentage organic matter in the eroded material, although they increased the organic matter content of the soil in the plots to some extent. This may be because these additions were very small in comparison with the total humus originally contained in the soil and because a large amount of the organic matter that was added decomposed very rapidly. Possibly after several more annual manure applications have been made, one may be able to detect a difference in the amount of humus in the eroded soil due to treatment. Even if this should be the case, however, it would be difficult to decide whether the differences could be ascribed to organic matter treatments or to some other cause. In general, the percentage humus in the eroded material decreased as the erosion losses increased. Consequently any increase in the percentage organic matter in the eroded material from manured plots may be due to decreased erosion. Inherent differences in the plots due to soil variation may also be a factor.

Studies of the nature of the organic material in the eroded and original soils suggest that certain fractions of the soil humus are more readily eroded than others. The organic matter of the eroded material had a greater percentage of nitrogenous complexes and hemicelluloses than the organic matter in the original soil. The fact that the eroded material had a narrower carbon-nitrogen ratio than the parent soil material is in agreement with the findings of Metzger and Hide (2) that the organic matter in poorly aggregated fractions of the soil had a somewhat narrower carbon-nitrogen ratio than that in larger aggregates. When erosion occurs, the small dispersed fractions of the soil are most readily washed away.

A preliminary report from the Marlboro erosion station (1) and data reported above indicate that soil losses and consequently organic matter and nitrogen losses from Collington sandy loam due to erosion may be reduced to a small extent by annual applications of manure and to a considerable extent by the use of a cover crop together with manure additions. Manure is most active in reducing losses during the summer months immediately after its addition to the soil (1, 3): this is the period of its most rapid decomposition and greatest abundance. The cover crop tends to conserve the soil during periods when it is otherwise left bare.

SUMMARY

Experiments were made on Collington sandy loam to determine organic matter and nitrogen losses due to erosion under various organic matter treatments, and to compare the amount and nature of the humus in the soil with that which is eroded away from the soil. It was found that the eroded material in most cases contained from three to eight times as much organic

matter and nitrogen as the soil itself.· The amount of organic matter and nitrogen in the eroded material depended upon the intensity of the rainfall, upon plot treatment, and upon the individual plot. During approximately $2\frac{1}{2}$ years the percentage organic matter in the soil lost by erosion was four to five times as great as that in the soil of the plots. From plots representing four annual treatments; namely, fertilizer, fertilizer + rye cover crop, fertilizer + 20 tons of stable manure, and fertilizer + rye cover crop + 20 tons of stable manure, averages of 1,185, 730, 950, and 415 pounds of organic matter per acre were lost during the $2\frac{1}{2}$-year period.

Soil eroded from plots contained greater percentages of nitrogenous complexes and hemicelluloses than the original soil, suggesting selective erosion of certain fractions of the organic matter.

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RELATION OF FIELD CAPACITY TO MOISTURE EQUIVALENT IN SOILS OF WEST VIRGINIA[1]

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Moisture equivalent is recognized as one of the important physical measurements of soil. Indirectly it has been used for estimating various soil moisture conditions, among which is field capacity. The field capacity has generally been considered as the water-retaining capacity of a soil one to five days after a rain or after an application of irrigation water. A rather comprehensive review of the literature on the relationship between moisture equivalent and field capacity has been made by Olmsted (5). The data from some of these investigations have been summarized graphically by Piper (6) and show that the ratio of field capacity to moisture equivalent is about unity in the vicinity of a moisture equivalent of 20 per cent; more than unity for moisture equivalents below 20 per cent; and less than unity for moisture equivalents above 20 per cent. It is evident that most of the data are from subhumid areas, where there usually is a dry layer below the wetted portion of the soil. Under these conditions true equilibrium can never be obtained, but within a relatively short time the movement becomes extremely slow. A somewhat different condition exists in the humid regions where the soil profile, during most of the year, is moist and in contact by capillary forces with the ground water. Slow attainment of moisture equilibrium and somewhat different values for the moisture content are to be expected under these conditions.

The relationship of moisture equivalent to field capacity is of interest from the standpoint of soil and water conservation. Since few or no data are available on this subject for soils of the humid region, information was obtained for certain of the important soils of West Virginia. Results are reported herein.

PROCEDURE

Moisture equivalents were determined by the method proposed by Goldbeck and Jackson (3, 7). Their method has been shown (2) to be in general agreement with the Briggs and McLane method (1) for determining moisture equivalent.

For determining field capacity, cylinders of galvanized iron, 6 inches in diameter and 14 inches long, were driven into the ground to a depth of 2 or 3 inches and were filled with water. Forty-eight hours after the water had disappeared from the surface, soil samples were collected for moisture determinations from the surface soil, from a layer 6 inches below the surface soil, and from a layer 6–12 inches below the surface soil.

The field work was carried out in the early spring after a 20-day period during which there was approximately 6 inches of rainfall, with a minimum of runoff. Temperatures were low and vegetation small. Losses of moisture by evaporation and transpiration were, therefore, at a minimum, and the soils should have been at or near field capacity. To determine whether the soils were at this level before the water was added to the cylinders, soil samples were collected for moisture determinations from a site immediately adjacent to the area which received excess water in the regular field-capacity determination.

RESULTS

In figures 1, 2, and 3 are shown the ratios of field capacity to moisture equivalent for the surface soil, for the layer 6 inches immediately below the surface soil, and for a layer 6–12 inches below the surface soil.

It is evident that the ratio increases with a decrease in moisture equivalent. The rate of change is small for soil with moisture equivalents in the range of about 12 to 35. For soils with a moisture equivalent of less than 12 the change is much more rapid. The general shape of the curves is the same for the different sampling depths. Slight variations are to be noted in that the average ratio of field capacity to moisture equivalent is unity at a moisture equivalent of 23 for the surface soil; unity at 21.5 for the 6-inch layer immediately below the surface soil; and unity at 20.5 for the layer 6–12 inches below the surface soil. This is in agreement with data by other investigators in that the ratio decreases slightly with depth. In general the subsoil is higher in clay, which may partly explain the decrease in ratio with depth.

If the curves are superimposed upon each other it is to be seen that those in figures 2 and 3 have virtually the same shape. The curve in figure 1 is about the same as the curves in figures 2 and 3 at the extremes, the remainder having a somewhat higher ratio. It is not surprising to find variation in individual soils, since the structure is disturbed when the soil is prepared for the moisture-equivalent determination. Screening the samples alters the pore distribution, the amount of change varying as the physical conditions of the soils vary as a result either of inherent characteristics or of past cultural treatments. Likewise, another possible source of error is the time required by different soils for establishment of equilibrium in the field-capacity determination. In general, however, the agreement is reasonably good.

Data for the three sampling depths are brought together in figure 4. Since the separate curves for the three sampling depths are essentially the same, grouping of all the data does not change the general shape of the curve.

In table 1 are shown the moisture contents of different soil sites 48 hours after an excess of water was added to the surface in comparison with adjoining sites which did not receive an excess of water. It should be remembered that the samples were taken after a period of rainfall, and the soils were at, or very near, field capacity.
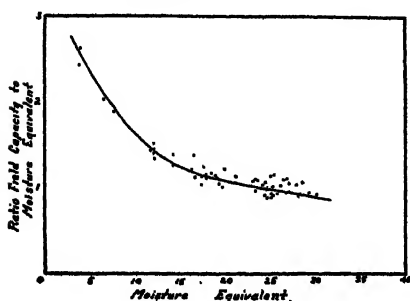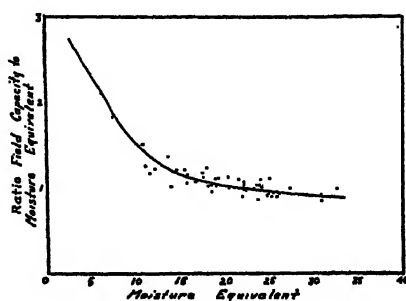
FIG. 1   FIG. 2

FIG. 1. SCATTER DIAGRAM SHOWING THE RATIO OF FIELD CAPACITY TO MOISTURE EQUIVALENT FOR SURFACE SOIL SAMPLES

FIG. 2. SCATTER DIAGRAM SHOWING THE RATIO OF FIELD CAPACITY TO MOISTURE EQUIVALENT FOR THE LAYER 6–12 INCHES BELOW THE SURFACE SOIL
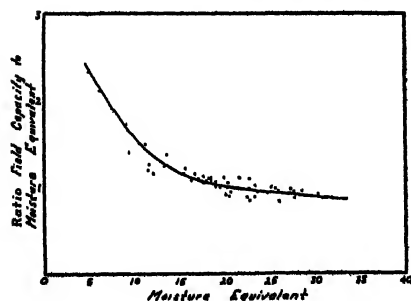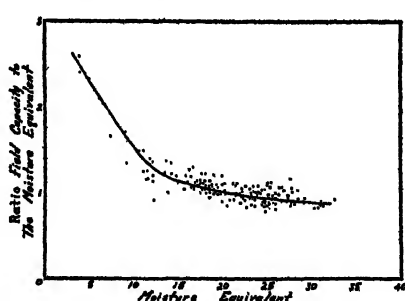
FIG. 3   FIG. 4

FIG. 3. SCATTER DIAGRAM SHOWING THE RATIO OF FIELD CAPACITY TO MOISTURE EQUIVALENT FOR THE LAYER 12–18 INCHES BELOW THE SURFACE SOIL

FIG. 4. SCATTER DIAGRAM SHOWING THE RATIO OF FIELD CAPACITY TO MOISTURE EQUIVALENT FOR ALL SAMPLING DEPTHS

From the data it is to be seen that the well-drained Gilpin, Westmoreland, and Wheeling soils have essentially the same moisture content 48 hours after application of an excess of water as the sites which did not receive water. On the other hand, Upshur clay, which is a very impermeable soil, still had water standing on the surface 48 hours after application. In the Holston and Monongahela soils, the moisture content 48 hours after application is higher than that of the adjoining areas which did not receive additional water. These soils are of terrace origin, and it is generally recognized that water moves

relatively slowly through the subsoil. In these soils about half of the 48-hour period was required for the added water to penetrate the soil. Consequently there had not been sufficient time for equilibrium to be established. Likewise, the Wheeling soils, which were sampled 24 hours after application of an excess

TABLE 1

Moisture content of soils from different locations sampled after a rainy period and 48 hours after application of an excess of water

SOIL TYPE	DEPTH SAMPLED	MOISTURE CONTENT		
		Moisture equivalent	After a rainy period	48 hours after application of excess water
	inches	*per cent*	*per cent*	*per cent*
Gilpin silt loam................	0–6	28.5	28.0	28.5
	0–5	22.5	21.5	21.8
	0–5	33.2	31.4	33.3
	0–7	25.0	25.4	23.2
Westmoreland silt loam..........	0–6	31.0	29.9	30.0
	0–5	22.8	23.2	22.1
	0–6	21.0	21.6	22.2
Wheeling fine sandy loam........	0–8	19.9	24.1	24.7
	0–7	12.0	15.6	16.0
	0–6	7.3	13.4	17.0*
	0–7	18.9	23.3	26.3*
	0–6	19.3	20.9	24.5*
Upshur clay....................	0–5	31.1	26.6	†
	0–4	26.9	28.0	†
	0–5	26.6	28.6	†
	0–6	29.7	34.2	†
Monongahela silt loam..........	0–5	27.9	29.9	34.7
	0–7	22.8	23.5	32.9
	0–6	23.0	24.6	27.7
Holston silt loam...............	0–6	23.6	23.7	27.2
	0–6	25.2	24.6	26.2

* Sampled 24 hours after application of an excess of water.
† Water standing on the surface 48 hours after application.

of water, contain a higher percentage of moisture than the areas which had not received the excess water.

From these data it is evident that there is considerable variation in the time required for different soils to reach a condition which approaches equilibrium after a rainfall or after an application of water. This is in agreement with data by other investigators. In this study soil samples were collected 48 hours after

the excess water had disappeared from the surface. It is highly probable that the length of time was not enough for equilibrium to be established in the impermeable Upshur soils.

DISCUSSION

It is evident that there is a general relationship between field capacity and moisture equivalent. Under the conditions of this experiment it was observed that after water was applied to a well-drained soil, the excess drained out within a relatively short time. Changes after 1–2 hours were small and reached a more or less constant value in 24–48 hours. In the impermeable soils, however, excess water applied to the surface did not penetrate for 2–3 days. Even after the excess water disappeared from the surface, equilibrium had not been established in 48 hours. Under these conditions, it is obvious that erroneous results of field capacity may be obtained unless sufficient time is allowed for equilibrium to become established before the soil samples are taken for moisture determinations. This is in agreement with the 1–5-day period suggested by other workers (5) as the time required for equilibrium to be established. It should be recognized that true equilibrium is seldom, if ever, reached in soils in contact with a changing water table or in soils which are continuously losing water by evaporation and transpiration.

The fact that the larger percentage of the excess water drains out of the soil within a relatively short time after a rain or after an application of water indicates that this movement is through the larger-sized pores. It is the larger-sized or the so-called noncapillary pores that are responsible for the rapid movement of water through soils and that determine to a considerable extent the infiltration rate of a particular soil, provided the surface condition does not limit the rate of water penetration. The tension required to empty the soil pores increases as the pores become smaller. The movement of moisture below field capacity is by capillarity and in general is slow.

Field capacity or similar determinations have been used as a basis for separating capillary pores from noncapillary pores. Actually there is no sharp line of demarcation between the two sizes. Recent data by Nelson and Baver (4) and others show that when a complete pF-moisture content curve is not available, an average tension of about pF 1.6 can be taken to represent the dividing point between capillary and noncapillary pores. The moisture in soils below pF 1.6 moves rapidly and is influenced largely by forces of gravity and only to a small extent by capillary forces. The tension at the moisture equivalent, which is also a reasonably good measure of the field capacity in soils texturally silt loams, is about pF 2.7. The tensions corresponding to pF 1.6 to 2.7 move much more slowly and are definitely affected by both capillary and gravitational forces, the effect of the former becoming more and more apparent as the tension approaches pF 2.7. Since the line of demarcation between the size of capillary and noncapillary pores is arbitrary, it seems logical that capillary pores should begin at the point where the pores cease to exert a

significant influence on the infiltration rate, even though there is still some water movement through them. Therefore, though the moisture held at field capacity can be taken as a measure of capillary porosity, a more logical measure of noncapillary porosity is at a tension of about pF 1.6, which has been shown to include the pores through which water moves rapidly as a result largely of the force of gravity. For a measure of the amount of water a soil will hold after a rain or after an application of water, field capacity of a value somewhat higher than pF 1.6 should be used, since in many soils appreciable movement of gravitational water occurs until this point is approached.

SUMMARY

The relation of moisture equivalent to field capacity in some soils of West Virginia was determined. The results may be summarized briefly as follows:

For the average of all sampling depths the ratio of field capacity to moisture equivalent is unity in the vicinity of a moisture equivalent of about 21 per cent; more than unity for moisture equivalents below 21 per cent; and less than unity for moisture equivalents above 21 per cent. The ratio decreases slightly with depth, but the shape of the curves for different depths is, in general, the same.

Well-drained soils come to a more or less constant moisture content within a short time after application of an excess of water; impermeable soils require a much longer time.

The possibilities and limitations of using field capacity or moisture equivalent, corrected for texture, in determining capillary porosity, are discussed in relation to the more precise methods for determining pore-size distribution.

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A METHOD OF PREPARING SOILS FOR PETROGRAPHIC ANALYSIS[1]

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Petrographic examination of soil minerals can be successfully carried out only after the particles have been cleaned of all extraneous material. The coating on the outside of soil mineral fragments not only obscures their optical characteristics but serves as a cementing agent that holds the particles together in aggregates and thus makes heavy liquid separations of mineral groups extremely difficult. The materials that coat the mineral fragments occurring in soils are generally organic matter, colloidal silica and aluminum, and iron oxides. The complete removal of these substances before any subsequent mineralogical analysis can be satisfactorily undertaken is imperative.

Various methods involving solvents of many kinds have been proposed from time to time. For a very complete review of the literature on this subject the reader is referred to the manual of Krumbein and Pettijohn.[3]

The requirements for any method should be: first, that the reactions involved be of such a nature as to preserve certain unstable minerals that might occur; second, that the coating and cementing materials be removed as rapidly and thoroughly as possible; and third, that the various operations involved be susceptible of routine manipulation. These requirements are all important when one considers any investigation requiring the examination of large numbers of soil samples.

One of the most common cementing materials encountered in soils is iron oxide in various degrees of hydration. The removal of this is one of the difficult problems in preparing soils for petrographic study.

Recently the writer found that nascent hydrogen produced by the action of oxalic acid on metallic aluminum in a soil suspension free of organic matter would reduce and dissolve rapidly the free iron oxide coating the soil particles, and that the iron in solution could be easily removed from the soil by washing by means of a centrifuge. In the process small amounts of silica, aluminum oxide, and titanium oxide are removed along with the iron oxide. The soil separates prepared by this method are in excellent condition for further study.

Many samples can be cleaned rapidly and a definite routine carried out. It is the purpose of this paper to describe this method in detail and to give examples of some of the characteristics of soil samples thus prepared.

METHOD

Procedure

Weigh 10 gm. of air-dry soil into a 600-ml. beaker, destroy organic matter by means of 10 per cent H_2O_2 (usually two 25-ml. treatments are sufficient), evaporate to dryness, make up to 500 ml. with distilled water, and stir well to loosen any soil adhering to the bottom of the beaker. Add 2 ml. of 50 per cent NaOH and boil gently for 5 minutes. Remove the beaker from the flame and allow it to cool slightly, add 10 gm. of oxalic acid and a weighed aluminum cylinder $2\frac{1}{2}$ x 2 x $\frac{3}{32}$ inches, and boil gently for 20 minutes, replacing water lost by evaporation. Remove the cylinder and place it in a 1.5-liter beaker which is to receive the washings containing the dissolved iron oxide. To the soil suspension, which contains some yellow ferrous oxalate, add 3 ml. of 10 per cent H_2O_2 and 3 ml. of N HCl,[4] boil 5 minutes, remove from the flame, add 10 gm. of NH_4Cl, and place on the steam bath to flocculate. After flocculation, transfer to 100-ml. centrifuge tubes and wash free of iron by means of 5 per cent NaCl solution in 0.001 N oxalic acid, placing the washings in the beaker containing the weighed aluminum cylinder. When the iron in solution is separated from the soil, wash the cleaned residue three to five times with alcohol saturated with sodium chloride and twice with acetone. Dry and weigh the cleaned soil, disperse it in a dilute solution of sodium carbonate at pH 8.0, and carry out the mechanical analysis.

If it is desired to determine the free iron oxide, aluminum oxide, titanium oxide, and silica removed by this treatment proceed as follows: To the beaker containing the weighed aluminum cylinder and washings, add 5 ml. of 10 per cent H_2O_2 and 20 ml. of N HCl and heat on the steam bath until the ferrous oxalate deposit on the aluminum cylinder is dissolved; remove the cylinder, and wash, dry, and weigh it. If any clay is present in the washings allow it

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[4] During the reduction of the iron some yellow ferrous oxalate is precipitated on the aluminum cylinder, part of which becomes detached and is found in the soil suspension after the removal of the cylinder. It was found that this was easily decomposed by hydrogen peroxide and hydrochloric acid. It is for this purpose that hydrogen peroxide and hydrochloric acid are added to the soil suspension after the removal of the cylinder in the course of the treatment. The aluminum cylinder in the beaker containing the washings is treated likewise for the same purpose.

It is necessary to analyze a sample of the aluminum used to make the cylinders. The metal used by the author contained 0.23 per cent SiO_2, 2.12 per cent Fe_2O_3, and no TiO_2. These constituents must, of course, be taken into account in determining the SiO_2 and Fe_2O_3, as well as the Al_2O_3 removed from the soil by the treatment.

The pH of the solution is 2.5 by the quinhydrone electrode and the total acidity is approximately 1.6 per cent in terms of oxalic acid.

to settle, decant off the clear solution, wash the clay with 5 per cent NaCl in 0.001 N oxalic acid, and add to the cleaned soil.

Evaporate the washings to slightly less than a liter, make up accurately to a liter, take 100-ml. aliquots for the determination of Fe_2O_3, Al_2O_3, TiO_2, and SiO_2. Place each 100-ml. aliquot in a casserole, add 5 ml. of concentrated HNO_3, evaporate to dryness, and proceed with the determination. Knowing then the weight of the aluminum cylinder before and after treatment and the composition of the metal it is possible to compute the amounts of SiO_2, Al_2O_3, Fe_2O_3, and TiO_2 removed from the soil by this treatment.

RESULTS

Three soil samples from a Hagerstown profile were cleaned by the above method. The mechanical analysis and amounts of silica and of aluminum, titanium, and iron oxides removed are set forth in table 1.

TABLE 1

Mechanical analysis of Hagerstown soil samples

Depth of Samples in Profile........................*inches*	16.25–25	25–36	36–51
	per cent	*per cent*	*per cent*
Coarse sand (1.0–0.5 mm.)....................	4.69	4.38	3.18
Medium sand (0.5–0.25 mm.)...................	1.78	1.68	1.45
Fine sand (0.25–0.10 mm.)....................	3.14	2.97	2.44
Very fine sand (0.10–0.5 mm.)................	13.81	13.06	10.34
Silt (0.05–0.002 mm.)........................	19.53	21.52	17.75
Clay (<0.002 mm.)..........................	42.44	43.12	50.36
SiO_2......................................	1.76	1.58	1.23‡
Al_2O_3....................................	1.05	1.30	1.28
Fe_2O_3....................................	6.95*	6.38†	7.58
TiO_2......................................	0.05	0.05	0.05
Loss on ignition.............................	4.50	4.55	4.77
Total..................................	99.70	100.59	100.43

* 94.8 per cent of the total iron in sample.

† 91.1 per cent of the total iron in sample.

‡ 96.4 per cent of the total iron in sample.

Upon microscopic examination the sands and silt prepared by this method were found to be excellent for petrographic study. The particles were clean and discrete, and no difficulty was encountered in making heavy liquid separations. As far as could be determined by means of the microscope no minerals had been attacked by the treatment. Work is in progress to determine whether any clays containing combined iron are attacked by this treatment. This work will be reported in a later paper where the chemical compositions of clays from various sources will be studied. Preliminary results seem to

indicate that iron-bearing clays are not attacked, but definite conclusions will be reserved until later.

SUMMARY

A method has been described for removing iron oxide, silica, and alumina, existing as coatings and cementing agents on soil grains, preparatory to making petrographic studies of soil minerals. This method involves the reduction of the iron oxide by means of nascent hydrogen and its solution by oxalic acid, after which it is easily removed by washing. This treatment removed about 94 per cent of the total Fe_2O_3 and small amounts of SiO_2, Al_2O_3, and TiO_2. The treatment is rapid, and produces excellent soil separates for subsequent petrographic study, apparently does not attack the soil minerals, and allows attention to a large number of samples at one time.

FOLIAR DIAGNOSIS IN RELATION TO SOIL HETEROGENEITY[1]

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The object of this investigation is to compare the nutrition with respect to the fertilizer elements nitrogen, phosphoric acid, and potash of similarly treated pairs of plots in a differentially fertilized greenhouse experiment with tomatoes.

The interpretation of certain data from our experiments carried out under field conditions has been criticized on the grounds that since only two plots received identical fertilizer treatment, the method is inadequate statistically for evaluating soil heterogeneity. Our point of view, on the other hand, is that this objection is founded on the traditional procedure of the use of final yields and of final yields only as the basis of comparison, and even then only in terms of probabilities.

The spirit of biology is opposed to the use of calculations of probability in such a manner as to submerge into an abstract quantity a specific property or properties possessed by the whole or any part of a living organism. Furthermore, the laws of great numbers are not applicable to a relatively small number, such as 100, and much less so to populations as small as four or five.

In the method of foliar diagnosis (5), however, the comparison between only two similarly fertilized plots may be made legitimately, because in this method soil heterogeneity is expressed not only in terms of the course of development of the plants as well as the final yields (2, 5), but also in terms of the course of nutrition with respect to the fertilizer elements added, which has been shown to be directly related to the course of development and the yields (3, 7). The emphasis is, accordingly, placed upon increasing the number of observations during the growth cycle rather than increasing the number of similarly treated plots.

The number of observations on cultivated plots cannot, in fact, be increased too much. In the experiment reported in this paper, the problem consists in discovering the effectiveness of two similar fertilizers. To this end, six experimental points have been determined for each plot, which show at a glance whether the nutrition of any two couplets with respect to the fertilizer elements added is identical or not. Moreover, since these six experimental points are known to be related to the development of the aerial and subter-

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ranean parts (3, 7), there exists, in effect, the equivalent of twelve observations on each plot, from which to determine the validity of the results.

No excuses, therefore, are offered for the fact that only two couplets in this experiment have received the same fertilizer, because the method of continuous observations during the growth cycle enables valid comparisons to be made which would be denied to a procedure depending upon yields alone.

It is, thus, much more rational to determine the comparative effects of a fertilizer from the course of events as indicated by the diagrams of foliar diagnosis than it would be to multiply the number of plots and then subject them to the calculation of probabilities. The multiplication of the number of plots, furthermore, tells us nothing about the soil factors influencing the efficacy of a fertilizer.

Observations based on yields alone tell us nothing about the real mode of nutrition producing these yields. Consequently, the agriculturist basing his conclusions on yields alone is frequently perplexed, as for example when an element, let us say nitrogen, is increased to two, three, or fourfold the basic application. A new experiment is necessary to determine whether phosphoric acid or potash might not then be the effective element lacking in the application.

Finally, the determination of nutritional deficiencies is always questionable if the material is not subjected to chemical analysis.

MATERIALS AND METHODS

The general plan of the greenhouse experiments has been outlined in a preceding paper (14). For the purpose of orientation the following pertinent facts are given.

Fertilizer treatments

The soil was a composted clay loam about 14 inches deep with a clay loam subsoil; it was tile drained. Plots were $5\frac{3}{4}$ feet wide and 8 feet long, and contained 12 plants in three rows of four plants lengthwise of the plot. The soil in the beds had been treated uniformly during 8 years before the plots were laid out, but previous to this period new soil from nearby fields had been added at several places to raise the level after installation of the tile drains used for steam pasteurization. No effort had been made to apply this uniformly. It may be assumed that frequent spading mixed the soil to some extent; it was apparent from the studies herein reported that uniformity of soil had not been brought about.

The plan of the fertilizer treatments is shown in figure 1, from which the relative position of similarly treated couplets can be determined. Sodium nitrate, superphosphate, and muriate of potash were the respective carriers of nitrogen, phosphoric acid, and potash, supplied in amounts equivalent to 41.7 gm. of N, 125.2 gm. of P_2O_5, and 43.1 gm. of K_2O per plot.[2] These quan-

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[2] Plots 4R, 4L, 15L, and 15R received twice this amount of N, and plots 8R, 8L, 19L, and 19R, biweekly additions of the unit quantity of N.

tities are approximately equal to 500 pounds of commercial nitrate of soda, 1300 pounds of 20 per cent superphosphate, and 150 pounds of 60 per cent muriate of potash to the acre.

Well-rotted horse manure (110 pounds per plot) was spaded into the soil just before steam pasteurization in the fall. The manure application contained 422.1 gm. of N, 274.9 gm. of P_2O_5, and 345.8 gm. of K_2O per plot. The

19L (RN)PK + manure	19R (RN)PK		20L PK	20R PK + manure
17L (4N)PK + manure	17R (4N)PK (not examined)		18L NK	18R NK + manure
15L (2N)PK + manure	15R (2N)PK		16L NP	16R NP + manure
13L NPK + manure	13R NPK		14L P	14R P + manure
11L PK + manure	11R PK	Walk	12L N	12R N + manure
9L NK	9R NK + manure		10L Manure	10R Nothing
7L NP	7R NP + manure		8L (RN)PK + manure	8R (RN)PK
5L P	5R P + manure		6L (4N)PK + manure	6R (4N)PK (not examined)
3L N	3R N + manure		4L (2N)PK + manure	4R (2N)PK
1L Nothing	1R Manure		2L NPK + manure	2R NPK

FIG. 1. PLAN OF GREENHOUSE PLOTS

plants were transferred from pots to the beds on March 15. Water was applied in equal quantities to each plot when required. Further details are given in preceding papers (4, 14).

Methods of sampling

The general principles upon which the method of sampling in investigations on foliar diagnosis is based have been described in earlier publications (5, 6, 7, 9, 10, 11). Healthy leaves from morphologically homologous positions on the stalk are sampled periodically.

TABLE 1

Relation of mean intensities and mean NPK-units to yields of couplets

PLOT	TREATMENT	INTEN-SITY (MEAN)	NPK-UNITS (MEAN)	YIELD	DIFFER-ENCE IN YIELD $(A - B)$	RELATIVE DIFFERENCE IN YIELD $\left(\dfrac{A - B}{A} \times 100\right)$
				pounds	*pounds*	*per cent*
Without manure						
10R—(A)	Nothing	6.42	62.20:32.06: 5.74	88.1	+16.3	+18.5
1L—(B)		5.96	66.72:26.90: 6.37	71.8		
12L—(A)	N	5.88	72.71:21.02: 6.27	64.4	−5.6	−8.7
3L—(B)		6.20	74.31:19.01: 6.68	70.0		
14L—(A)	P	5.79	61.07:33.92: 5.00	43.3	−38.8	−89.6
5L—(B)		5.86	61.34:32.63: 6.02	82.1		
16L—(A)	NP	6.12	67.40:27.37: 5.23	30.9	−59.7	−193.2
7L—(B)		6.28	68.97:25.55: 5.48	90.6		
18L—(A)	NK	5.80	74.94:16.79: 8.23	95.6	+19.5	+20.4
9L—(B)		5.86	75.85:15.10: 9.05	76.1		
20L—(A)	PK	5.71	61.95:27.19:10.84	98.8	+81.7	+82.7
11R—(B)		4.80	60.52:27.02:12.46	17.1		
2R—(A)	NPK	6.10	71.04:21.21: 7.75	113.8	+12.8	+11.2
13R—(B)		5.87	69.95:20.88: 9.16	101.0		
4R—(A)	(2N)PK	6.46	71.58:20.96: 7.46	107.3	+73.2	+68.2
15R—(B)		5.80	74.40:15.98: 9.62	34.1		
8R—(A)	(RN)PK	6.77	75.37:16.58: 8.04	104.5	+41.1	+39.3
19R—(B)		6.60	73.20:19.77: 7.02	63.4		
With manure						
10L—(A)	Manure	7.17	62.58:21.66:15.76	113.2	−14.2	−12.5
1R—(B)		7.53	66.95:18.12:14.93	127.4		
12R—(A)	N + Manure	7.64	69.92:16.31:13.77	121.9	−8.0	−6.6
3R—(B)		7.59	72.04:14.17:13.79	129.9		
14R—(A)	P + Manure	6.57	63.81:21.13:15.06	113.5	−19.3	−17.0
5R—(B)		7.30	66.12:17.32:16.58	132.8		
16R—(A)	NP + Manure	7.36	67.24:18.52:14.23	117.9	−27.5	−23.3
7R—(B)		7.30	70.48:17.30:12.21	145.4		
18R—(A)	NK + Manure	7.94	68.33:18.00:13.66	120.5	+32.7	+27.1
9R—(B)		7.06	70.61:13.73:15.66	87.8		

TABLE 1—*Concluded*

PLOT	TREATMENT	INTEN-SITY (MEAN)	NPK-UNITS (MEAN)	YIELD	DIFFER-ENCE IN YIELD $(A - B)$	RELATIVE DIFFERENCE IN YIELD $\left(\dfrac{A - B}{A} \times 100\right)$
				pounds	pounds	per cent
		With manure—Concluded				
20R—(A)	PK + Manure	7.85	62.26:20.27:17.47	129.3	+64.7	+50.0
11L—(B)		6.17	62.00:21.68:16.31	64.6		
2L—(A)	NPK + Manure	7.54	68.40:14.21:17.39	121.8	+6.9	+5.7
13L—(B)		7.77	66.07:16.34:17.58	114.9		
4L—(A)	(2N)PK + Manure	7.00	69.97:16.38:13.65	115.5	+20.2	+17.5
15L—(B)		8.02	68.28:14.89:14.87	95.3		
8L—(A)	(RN)PK + Manure	7.83	71.22:13.89:14.89	120.5	+20.9	+17.3
19L—(B)		8.56	70.25:14.72:15.03	99.6		

In the present experiment the fifth leaf from the base was sampled in the manner described below from all plants on a plot at three sampling dates: April 5, April 29, and May 27. Two or three leaflets were taken on one side of the midrib of the leaf at the first sampling; at the second sampling, the leaflets opposite those removed at the first sampling, and at the last sampling, the remaining lateral leaflets together with the terminal leaflets were taken.

It is desirable to extend the period of observations as late as possible in the growth cycle. In the present experiment, however, a fourth sampling was not possible because of the senescence of the fifth leaf on many of the poorly nourished plants.

Analytical methods

The samples were dried and ground to a fine powder in the manner already described (5).

The analytical methods used were those of the Association of Official Agricultural Chemists (1), and were such as to give the total nitrogen, the total phosphoric acid, and the total potash present in the leaf at the moment of sampling, irrespective of the form in which each was present. This procedure is the only valid one and follows logically from the concepts involved in the method of foliar diagnosis (5).

PRESENTATION OF RESULTS

Yields of duplicate plots

Table 1 shows the yield of fruit in pounds from each plot together with the actual difference and also the relative percentage difference between the plots in each similarly treated couple.

TABLE 2

Course of nutrition of leaves with respect to nitrogen, phosphoric acid, and potash

SAMPLING DATE	PLOT	MINERAL CONTENT OF DRIED FOLIAGE				COMPOSITION OF THE NPK-UNIT		
		N (M_x)	P_2O_5 (M_y)	K_2O (M_z)	$N + P_2O_5 + K_2O$ ($M_x + M_y + M_z$) (s)	X $\left(100 \times \dfrac{Ex}{S}\right)$	Y $\left(100 \times \dfrac{Ey}{S}\right)$	Z $\left(100 \times \dfrac{Ez}{S}\right)$
Without manure								
Apr. 5 {	10R	3.96	1.87	1.49	7.32	71.81	20.10	8.09
	1L	4.08	1.57	1.55	7.20	74.59	16.96	8.45
Apr. 29 {	10R	2.90	2.50	0.69	6.09	63.23	32.91	4.48
	1L	2.92	1.99	0.74	5.65	67.62	27.25	5.13
May 27 {	10R	2.14	3.07	0.65	5.86	51.58	43.78	4.64
	1L	2.12	2.25	0.68	5.05	57.97	36.50	5.53
Apr. 5 {	12L	4.42	1.18	1.45	7.05	79.59	12.59	7.82
	3L	4.72	1.32	1.58	7.62	79.01	13.09	7.90
Apr. 29 {	12L	3.14	1.60	0.83	5.57	72.40	21.86	5.74
	3L	3.42	1.49	0.84	5.75	75.08	19.42	5.50
May 27 {	12L	2.52	1.84	0.67	5.03	66.14	28.61	5.25
	3L	2.72	1.63	0.87	5.22	68.90	24.51	6.59
Apr. 5 {	14L	3.90	1.89	0.85	6.64	73.98	21.20	4.82
	5L	3.80	1.83	1.27	6.90	72.21	20.58	7.21
Apr. 29 {	14L	2.38	2.39	0.67	5.44	59.61	35.40	4.98
	5L	2.50	2.35	0.75	5.61	60.69	33.84	5.47
May 27 {	14L	1.84	2.83	0.65	5.32	49.61	45.18	5.20
	5L	1.82	2.61	0.64	5.07	51.12	43.49	5.39
Apr. 5 {	16L	4.40	1.47	1.14	7.01	78.56	15.44	6.00
	7L	4.50	1.61	1.10	7.21	77.87	16.46	5.67
Apr. 29 {	16L	2.74	1.92	0.66	5.32	68.01	27.24	4.75
	7L	3.16	2.01	0.88	6.06	68.45	25.83	5.72
May 27 {	16L	2.00	2.39	0.59	5.98	55.63	39.44	4.93
	7L	2.50	2.39	0.70	5.59	60.59	34.36	4.05
Apr. 5 {	18L	4.52	1.11	2.07	7.70	77.98	11.38	10.64
	9L	4.48	1.05	1.84	7.37	79.31	10.97	9.72
Apr. 29 {	18L	3.08	1.11	1.00	5.19	76.28	16.33	7.39
	9L	3.34	1.07	1.29	5.70	76.58	14.58	8.84
May 27 {	18L	2.42	1.31	0.77	4.50	70.58	22.68	6.74
	9L	2.42	1.13	0.97	4.52	71.66	19.75	8.59
Apr. 5 {	20L	3.68	1.39	2.10	7.17	71.72	16.08	12.20
	11R	2.80	1.38	1.55	5.73	68.64	20.00	11.36
Apr. 29 {	20L	2.20	1.77	1.29	5.26	60.51	28.89	10.60
	11R	1.90	1.29	1.36	4.55	61.96	24.85	13.19
May 27 {	20L	1.70	1.96	1.03	4.69	53.64	36.64	9.72
	11R	1.36	1.63	1.15	4.14	50.93	36.23	12.84

TABLE 2—*Continued*

SAMPLING DATE	PLOT	MINERAL CONTENT OF DRIED FOLIAGE				COMPOSITION OF THE NPK-UNIT		
		N (M_x)	P₂O₅ (M_y)	K₂O (M_z)	N + P₂O₅ + K₂O ($M_x + M_y + M_z$) (s)	X ($100 \times \frac{Ex}{S}$)	Y ($100 \times \frac{Ey}{S}$)	Z ($100 \times \frac{Ez}{S}$)
					Without manure—Concluded			
Apr. 5	2R	4.36	1.23	1.78	7.37	77.57	12.96	9.46
	13R	4.28	1.39	2.07	7.74	74.80	14.42	10.78
Apr. 29	2R	3.18	1.56	1.08	5.82	71.86	20.88	7.25
	13R	2.98	1.29	1.13	5.40	72.98	18.76	8.26
May 27	2R	2.40	1.89	0.83	5.12	63.70	29.76	6.54
	13R	1.98	1.59	0.90	4.47	62.08	29.46	8.46
Apr. 5	4R	4.60	1.21	1.87	7.68	78.26	12.23	9.51
	15R	4.54	1.10	2.00	7.64	78.42	11.26	10.32
Apr. 29	4R	3.32	1.60	0.98	5.90	72.80	20.78	6.42
	15R	3.24	1.05	1.29	5.58	76.32	14.60	9.08
May 27	4R	2.72	2.15	0.92	5.79	63.68	29.86	6.46
	15R	2.08	1.13	0.97	4.18	68.41	22.08	9.51
Apr. 5	8R	4.82	1.23	2.16	8.21	77.84	11.73	10.43
	19R	4.62	1.54	1.63	7.79	76.76	15.16	8.08
Apr. 29	8R	3.88	1.32	1.31	6.51	76.79	15.48	7.73
	19R	3.64	1.59	1.13	6.36	73.97	19.18	6.85
May 27	8R	3.08	1.64	0.86	5.58	71.49	22.55	5.96
	19R	2.96	1.81	0.88	5.65	68.87	24.99	6.14
					With manure			
Apr. 5	10L	3.96	1.35	3.63	8.94	67.80	13.65	18.54
	1R	4.42	1.46	3.26	9.14	70.63	13.82	15.55
Apr. 29	10L	2.88	1.75	1.91	6.54	64.24	23.07	12.68
	1R	3.32	1.65	2.20	7.17	67.01	19.77	13.22
May 27	10L	2.14	1.83	2.07	6.04	55.69	28.26	16.05
	1R	2.62	1.45	2.23	6.30	63.20	20.76	16.03
Apr. 5	12R	4.66	1.08	3.05	8.79	75.05	10.30	14.65
	3R	4.82	1.24	3.29	9.35	73.73	11.24	15.03
Apr. 29	12R	3.70	1.50	2.45	7.65	69.54	16.70	13.76
	3R	3.66	1.27	2.31	7.24	71.76	14.71	13.53
May 27	12R	2.90	1.65	1.92	6.47	65.18	21.92	12.91
	3R	3.08	1.22	1.87	6.17	70.62	16.57	12.81
Apr. 5	14R	3.68	1.01	3.49	8.18	69.16	11.28	19.57
	5R	4.34	1.42	3.16	8.92	70.85	13.73	15.41
Apr. 29	14R	2.60	1.67	1.70	5.97	63.45	24.19	12.36
	5R	3.00	1.28	2.32	6.60	67.39	17.03	15.58
May 27	14R	2.18	1.75	1.65	5.58	58.83	27.91	13.26
	5R	2.42	1.44	2.52	6.38	60.13	21.20	18.67

TABLE 2—*Concluded*

SAMPLING DATE	PLOT	MINERAL CONTENT OF DRIED FOLIAGE				COMPOSITION OF THE NPK-UNIT		
		N (M_x)	P$_2$O$_5$ (M_y)	K$_2$O (M_z)	N + P$_2$O$_5$ + K$_2$O $(M_x + M_y + M_z)$ (s)	X $\left(100 \times \frac{Ex}{S}\right)$	Y $\left(100 \times \frac{Ey}{S}\right)$	Z $\left(100 \times \frac{Ez}{S}\right)$
With manure—Concluded								
Apr. 5	16R	4.52	1.20	3.73	9.45	71.26	11.21	17.53
	7R	4.60	1.41	3.04	9.05	72.52	13.20	14.28
Apr. 29	16R	3.24	1.65	1.92	6.81	67.65	20.36	11.99
	7R	3.42	1.51	1.87	6.80	70.21	18.32	11.47
May 27	16R	2.48	1.60	1.74	5.82	62.81	24.01	13.18
	7R	2.98	1.49	1.58	6.05	68.72	20.40	10.88
Apr. 5	18R	4.66	1.31	2.20	8.17	76.48	12.77	10.75
	9R	4.46	1.25	3.97	9.68	70.52	11.32	18.16
Apr. 29	18R	3.64	1.45	2.65	7.74	68.80	16.27	14.93
	9R	3.46	1.09	1.94	6.49	73.91	13.74	12.35
May 27	18R	3.08	2.17	2.65	7.90	59.72	24.96	15.32
	9R	2.64	1.07	2.16	5.87	67.40	16.12	16.48
Apr. 5	20R	4.26	1.30	4.17	9.73	67.91	12.28	19.81
	11L	3.74	1.39	2.93	8.06	68.83	15.11	16.06
Apr. 29	20R	3.02	1.69	2.68	7.39	62.68	20.73	16.59
	11L	2.52	1.31	2.00	5.83	64.70	19.97	15.33
May 27	20R	2.30	1.92	2.20	6.42	56.20	27.79	16.01
	11L	1.50	1.45	1.68	4.63	52.49	29.98	17.53
Apr. 5	2L	4.36	1.18	3.73	9.27	70.63	11.36	18.01
	13L	4.46	1.29	3.84	9.59	69.99	12.02	17.99
Apr. 29	2L	3.20	0.95	2.87	7.02	69.30	12.14	18.56
	13L	3.20	1.47	3.07	7.74	64.21	17.43	18.36
May 27	2L	2.76	1.37	2.21	6.34	65.27	19.14	15.58
	13L	2.52	1.30	2.16	5.98	64.03	19.57	16.40
Apr. 5	4L	4.54	1.24	2.84	8.62	74.15	12.00	13.85
	15L	4.66	1.23	4.17	10.06	70.25	11.01	18.74
Apr. 29	4L	3.46	1.48	2.70	7.64	67.27	17.05	15.68
	15L	3.50	1.20	2.87	7.59	68.89	14.23	16.88
May 27	4L	2.80	1.39	1.56	5.75	68.50	20.09	11.41
	15L	2.84	1.41	2.16	6.41	65.70	19.37	14.93
Apr. 5	8L	4.62	1.23	3.08	8.93	73.85	11.45	14.69
	19L	4.76	1.51	3.70	9.97	70.44	13.21	16.35
Apr. 29	8L	3.78	1.28	2.67	7.73	70.87	14.22	14.91
	19L	4.14	1.42	2.84	8.40	71.02	14.43	14.54
May 27	8L	3.22	1.26	2.36	6.84	68.96	15.98	15.06
	19L	3.48	1.40	2.39	7.27	69.29	16.51	14.20

Composition of the dried leaf material

The course of nutrition of morphologically homologous leaves with respect to nitrogen, phosphoric acid, and potash is given in table 2. As defined in preceding papers (5, 11), the intensity of nutrition is the sum of the percentages of N, P_2O_5, and K_2O in the dried foliage at the moment of sampling; the *NPK-unit* is the proportion which N, P_2O_5, and K_2O, respectively, expressed as milligram equivalents in 100 gm. of dried foliage, each represents in their milligram equivalent total, taken as 100. This NPK-unit may be represented graphically on an equilateral triangle, each side of which equals 100 (15).

DISCUSSION AND INTERPRETATION OF RESULTS

Comparison of characteristics of foliar diagnosis of similarly treated plots from a uniform and from a heterogeneous soil

It has been established (2, 7, 9) that when soils of two similarly treated plots are relatively homogeneous as deduced from similar developments and yields of the plants growing thereon, duplicate pairs will have similar foliar diagnoses, and when the soils of two similarly treated plots are heterogeneous as indicated by widely different developments and yields of the plants growing thereon, they will have widely dissimilar foliar diagnoses. Consequently, markedly dissimilar foliar diagnosis of plants of the same species from plots treated alike under otherwise uniform external conditions is an indication of the heterogeneity of the soils of the two plots under consideration, and may result not only from differences with respect to chemical composition but also from physical differences that may lead to differences in the supply of water or air to the roots. The net effect, then, is not only that of the soil *per se*, but also that of the soil in inhibiting or furthering the absorption of an element.

Relative percentage difference in yield of couplets

The changes in the signs ($+$, $-$) in table 1 show that the differences in yields of duplicate plots are not produced by any factor operating uniformly over the whole area. Thus, in the unmanured series there are six, and in the manured series five, plots having even numbers (i.e., plots to the right of the walk), in which the yield is greater ($+$) than that of its corresponding duplicate in the odd-numbered series (plots to the left of the walk); in the remaining three plots in the unmanured series and four in the manured series, the yield of the even-numbered duplicate is lower ($-$) than that of the corresponding odd-numbered plots. In three couplets only are the relative differences in yield $\left(\dfrac{A - B}{A} \times 100\right)$ less than 10 per cent, which may be regarded as falling within the degree of approximation that would occur in a relatively uniform soil. In the remaining couplets the relative difference in yields ranges from -193.2 to $+82.7$ per cent, indicating that greater differences exist in the soil of these couplets. The greatest relative difference in yield between a couplet is given by NP (plots 16L and 7L).

With one exception (NK + m, plots 18R and 9R) the relative differences in yields between couplets in the manured series is much lower than in the corresponding plots in the unmanured series. Manure additions, therefore, have operated to reduce the original differences in the soil of couplets. Furthermore, with one exception the sign (+ or −) of similarly commercially fertilized plots in the manured series is identical with that in the unmanured series, showing that the same soil characters were preserved in the preparation of an individual bed.

Course of nutrition during growth cycle

General characteristics of intensities of nutrition. In the unmanured series with one exception the intensity of nutrition—i.e., N + P_2O_5 + K_2O—of the higher-yielding plot is greater than that of its lower-yielding companion, during either the whole or the greater part of the growth cycle. The exception is NK (plots 18L and 9L), in which little difference occurs at any time. Furthermore, the intensities of all couplets fall below that of the optimum (NP + manure, plot 7R) throughout the whole cycle.

In the manured series there are three exceptions to the generalization that the intensity of nutrition of the higher-yielding plot in a couplet is greater than that of the lower-yielding companion. These plots are the three complete fertilizer plots (with manure). In these couplets, however, the intensity of the higher-yielding plot is always displaced nearer to the value of the optimum throughout the whole cycle. These cases present an example of injury to yields caused by too great an intensity.

General characteristics of NPK-equilibrium values. Much greater variation in the NPK-unit values between couplets is noted than between those for the intensities. The equilibrium between N − P_2O_5 − K_2O, therefore, is, in general, of more significance in determining differences in yield than is the intensity, unless the latter is abnormally low.

Mean intensities and mean NPK-units of couplets. The mean values indicate the resultant of the nutritional factors with respect to the added fertilizer elements that have operated during the growth cycle to affect the differences in yields.

The value of the mean for the optimum intensity (NP + manure, plot 7R) is 7.30. But the highest value for the intensity in the unmanured series is only 6.77 in (RN)PK, plot 8R. An adequate intensity is consequently a necessary condition for high yields. Although the order of yields does not follow the identical order of the intensities, nevertheless, the lowest-yielding plot PK (plot 11R) is associated with the lowest mean value for the intensity, namely 4.80, of any of the plots and is followed by the next lowest yielding plots 2N(PK) (plot 15R) and P (plot 14L) with the next lowest intensities of 5.80 and 5.79 respectively.

On the other hand, the next to the highest mean value for the intensity in the unmanured series (RN)PK (plot 19R) with a value of 6.60 is accompanied

by a relatively low yield. But as already pointed out, intensity alone is not the only factor to be considered; the relations (ratios) between the elements also must be taken into account. In the plants on this plot, 19R, we shall find that the equilibrium is poor.

In the manured series, the mean values of the intensities range between 6.17 and 8.56. In this series also the lowest yielding plot, PK + manure, 11L, has the lowest intensity of any of the manured plots. But the highest mean value of 8.56 is not associated with the plants from the highest-yielding plot, which has a lower value of 7.30. Intensities above 7.90 have resulted in a marked reduction of yields below that of the optimum. The two highest-yielding plots have identical mean values of 7.30. The next seven lower-yielding plots have intensities above this value, followed by three still lower yielding plots with lower values than that of the optimum, then by two low-yielding plots with the highest values for intensity and lastly by the two lowest-yielding plots of this (manured) series with low intensity values.

The conclusion to be drawn from these facts is that a mean value for the intensity not too far above optimum is less injurious to yields than are intensities well above or well below the optimum.

Relative to the mean values for the optimum equilibrium, 70.5:17.3:12.2, the values for the quota of K_2O in the low-yielding unmanured series are too low except in one plot, and too high for P_2O_5 in all but four plots. With respect to the values for N, eight plots have values below the optimum and the remainder values above it.

Keeping in mind the fact that a fertilizer intervenes in the nutrition of a plant to affect a change in the intensity or in the equilibrium between the elements or in both simultaneously, let us now examine the causal factors producing the difference in yields of like treated pairs.

Nothing Plots 10R and 1L. A more favorable displacement of the intensity of nutrition of the higher-yielding plot toward the optimum overbalances a less favorable $N - P_2O_5 - K_2O$ equilibrium.

N Plots 12L and 3L. The higher-yielding plot is associated with an increase of the intensity nearer the optimum and with a displacement of the equilibrium toward the position of the optimum by more favorable values for P_2O_5 and K_2O.

P Plots 14L and 5L. The higher-yielding plot has a slightly more favorable intensity, and the $N - P_2O_5 - K_2O$ equilibrium is displaced toward the position of the optimum because of more favorable values for P_2O_5 and K_2O.

NP Plots 16L and 7L. In these treatments also the higher yield accompanies a somewhat higher value for the intensity and a shift toward the position of the optimum by more favorable values for N, P_2O_5, and K_2O.

NK Plots 18L and 9L. In this couplet the higher-yielding plot has a slightly lower intensity; but a difference of 0.06 unit should not be overemphasized as a contributing factor. Rather the difference favoring the higher-yielding plot is a displacement of the equilibrium toward the position of the optimum by more favorable quotas of N and P_2O_5.

PK Plots 20L and 11R. The very low yielding plot has, as already stated, an extremely low value for the intensity. Although the equilibrium of the higher-yielding plot relative to that of the lower is displaced slightly toward that of the optimum, the predominant factor producing differences in yields in these plots is the great difference in the intensities.

(2N)PK Plots 4R and 15R and NPK Plots 2R and 13R. As in the case of the no-treatment plots a more favorable intensity of nutrition of the higher-yielding plots in relation to that of the optimum has overbalanced a relatively small displacement away from the optimum equilibrium.

(RN)PK Plots 8R and 19R. The higher-yielding plot is associated with a higher intensity and with a somewhat more favorable displacement of the equilibrium toward that of the optimum.

Manure Plots 10L and 1R. The higher-yielding plot is associated with a higher but somewhat less favorable intensity with respect to the optimum, but with a displacement toward the position of the optimum equilibrium by more favorable quotas of N, P_2O_5, and K_2O.

N + Manure Plots 12R and 3R. The higher-yielding plot has a slightly lower intensity of nutrition although nearer to that of the optimum. The relative difference in the yields, however, is small.

P + Manure Plots 14R and 5R. The value for the intensity of the higher-yielding plot is identical with the optimum. The $N - P_2O_5 - K_2O$ equilibrium of the higher yield is associated with values for N and P_2O_5 nearer to those of the optimum.

NP + Manure Plots 16R and 7R. Plot 7R is the highest-yielding plot in this experiment. The values for the intensity and NPK-units are, therefore, the optimum with which all other values are compared. The intensity of the lower-yielding plot 16R is slightly higher than optimum, and the quotas for P_2O_5 and K_2O are too high and that of N is too low.

NK + Manure Plots 18R and 9R. The intensity of the higher-yielding plot is higher and well above optimum; with respect to the $N - P_2O_5 - K_2O$ equilibrium, the higher-yielding plot is displaced, relative to that of the lower, nearer the position of the optimum by more favorable quotas of P_2O_5 and K_2O.

PK + Manure Plots 20R and 11L. The intensity of the very low yielding plot is, as already noted, well below the optimum. The displacement of the equilibrium of the higher-yielding plot is toward the position of the optimum because of more favorable quotas with respect to N and P_2O_5.

NPK + Manure Plots 2L and 13L. The intensity of the higher-yielding plot is lower but more favorably displaced toward the optimum. The shift in the equilibrium is also toward the position of the optimum by more favorable quotas of N and K_2O.

(2N)PK + Manure Plots 4L and 15L. The lower-yielding plot is associated with an intensity much above the optimum and with an equilibrium displaced away from that of the optimum by less favorable quotas of N, P_2O_5, and K_2O.

(RN) + Manure Plots 8L and 19L. The intensities of the plants growing

on both plots is well above optimum, the lower-yielding plot having the higher value—the highest of any of the plots in this experiment. This abnormally high value for the intensity has offset a somewhat more favorable equilibrium.

FOLIAR DIAGNOSIS AND MICRONUTRIENT ELEMENTS

The differences in yields of similarly treated pairs of plots on this soil—Hagerstown clay loam—are satisfactorily explained in terms of the differences in their intensities of nutrition and equilibrium values with respect to the fertilizer plastic elements in relation to the optimum.

Provided the intensity is sufficient, the equilibrium with respect to $N - P_2O_5 - K_2O$ is the predominant factor producing the higher yield. When, however, the intensity is well below or well above the optimum value, this factor may overshadow a more favorable equilibrium.

Since a relatively small displacement in the equilibrium between the plastic elements has been shown in this and preceding investigations on foliar diagnosis on this Hagerstown soil to cause relatively large differences in yields, it follows, as a corollary, that in all investigations on foliar diagnosis, search may be made for an oligoelement as a causal factor only when, with sufficient intensity of nutrition, the observed differences cannot be explained by a displacement of the equilibrium with respect to $N - P_2O_5 - K_2O$ (15).

It is not necessary, in general, to determine calcium and magnesium, for our investigations (8, 12, 13), have shown that the direction in which these elements affect the equilibrium between $N - P_2O_5 - K_2O$ is known. As the values for potash increase, those for calcium and magnesium decrease, and *vice versa*. It is possible that later investigations may indicate the manner in which other elements affect this equilibrium between the dominant, plastic elements.

SUMMARY

In a differentially fertilized greenhouse experiment with tomatoes, the nutritional factors producing differences in yields between similarly fertilized pairs of plots have been examined by the method of foliar diagnosis.

The alleged invalidity of the use of only two similarly treated plots in investigations on foliar diagnosis is discussed and the point of view emphasized that the method establishes the efficacy of a fertilizer by increasing the number of observations rather than the number of similarly treated plots.

Examination of the relative percentage difference in yields between pairs of similarly treated plots indicates the absence of any uniform soil factor. These differences range from -193 to $+82$ per cent in fifteen of the couplets and are less than 10 per cent in only the three remaining pairs, showing that only in the latter are the soils of similarly treated pairs relatively uniform. Smaller relative percentage differences in the yields of duplicate plots in the manured series than in the corresponding pairs of the unmanured series indicate that manure has tended to reduce the effect of the original soil differences.

The effect of a fertilizer on yields may be the result of its effect on the in-

tensity of nutrition or on the physiological relations among the elements as expressed by the equilibrium among them or on both values simultaneously. With respect to these values, the results indicate:

The intensity of the higher-yielding duplicate is nearer the value of the optimum than its lower-yielding companion and in most cases the value is higher.

Although the values for the intensities of nutrition of individual plots do not follow the exact order of yields, the generalization may be made that low intensities are associated with low yields, and high intensities with high yields. In other words, a sufficient intensity is necessary for high yields. Hence an intensity above optimum values has a less injurious effect on yields than has one below optimum.

With a sufficient intensity of nutrition the determining factor causing differences in yields between duplicates is the relative displacement in the N—P_2O_5—K_2O equilibrium, indicated by an approach to the value of the optimum by the higher-yielding duplicate. Much higher values for the intensity, however, which approach the values for the optimum may over-balance a recession of the equilibrium value from that of the optimum.

The position of foliar diagnosis investigations in relation to the micro-nutrient elements is defined.

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SOME PHYSICOCHEMICAL ASPECTS OF SOIL AGGREGATES[1]

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Aggregate stability, which is influenced by several external factors, is probably determined by the electrical nature of the component parts and the ability of the soil constituents to resist forces that would tend to remove the individual units of the aggregate from the center of the electrical sphere of influence. The force that binds the aggregate is likely determined by the strength of the electrical fields radiating from the individual soil particles and by the closeness of contact between particles making up the aggregate. Furthermore, dispersion of soil aggregates would seem to be possible only when the force of attraction between soil particles becomes less than the force of attraction between soil particles and the water or other dispersing medium plus any additional external force to which the soil aggregates might be subjected. Thus, swelling, which would influence the distance between particles; zeta potential, which would influence the radius of the electric field; solubility of the adsorbed liquid layer in the dispersing medium; and ability of the soil particles to resist wetting, which would alter the attraction between the soil particles and the dispersing medium, should influence the ease of dispersion. The influence of various organic liquids on soil aggregates, either alone or as a treatment prior to placing of the aggregates in water, would be in part to alter the degree of expression of the foregoing factors.

Various explanations have been offered for the union of negative soil particles into aggregates. Russell (10) suggested the following mechanism for the binding of two negatively charged particles: particle-dipole (water)-cation-dipole (water)-particle. He observed that crumb formation is limited to particles with considerable base-exchange capacity and occurs when there is an appreciable dissociation of cations at the surface. Sideri (11) proposed oriented adsorption of clay on sand and of humus on clay. He explained the development of the force of attraction between particles in aggregates as resulting from the drawing together of the colloidal particles during the process of aggregate formation which leads to a deformation of the ionic envelope around the colloidal particles. The consequent decrease in volume of the ionic layer

decreases the zeta potential and the degree of dissociation and consequently must decrease the solubility and the exchange capacity, according to Sideri. Myers (8) suggested polar adsorption as a possible explanation for the physico-chemical interaction between colloidal clay and colloidal organic matter. Baver and Hall (2) indicated that the high resistance to dispersion of H-humus after drying and the alteration of the system with standing suggest the orientation of H-humus particles with respect to one another. Baver (3) points out that Henin ascribed considerable significance to the orientation of clay particles in secondary particle formation. More recently Ensminger and Giese-king (4) presented data indicating that protein molecules are adsorbed by the clay particles as cations.

The favorable influence of organic matter on the stability of aggregates has been attributed, by several investigators (2, 8, 11), to the slowly reversible character of dehydrated organic colloids. Likewise Lutz (7) has explained the favorable role of iron in the aggregate stability of lateritic soils on the basis of the slow reversibility of dehydrated iron compounds.

TABLE 1

Mechanical analysis of soils used in aggregate study

SOIL SERIES	MECHANICAL ANALYSIS		
	Sand	Silt	Clay
	per cent	*per cent*	*per cent*
Geary..............................	26.4	29.0	44.6
Bates...............................	56.1	14.0	29.9
Cherokee...........................	19.7	44.0	36.3
Garden City*........................	37.7	33.0	29.3

* Series not identified.

MATERIALS AND METHODS

The soil series used in this experiment were from southeastern Kansas (Cherokee and Bates), from the college agronomy farm (Geary), and from the Garden City Branch Experiment Station in southwestern Kansas (series not known). The average rainfall for the areas has been about 40, 31, and 19 inches, respectively. All soils were formed under grass and have been under cultivation for many years. The samples had been in the laboratory for several months. As used, all soils were air-dry and had been put through a 2-mm. U. S. standard sieve. The soils from the agronomy farm were put through the sieve before being air-dried, whereas the other soils were all air-dried before being sieved. The mechanical analyses by the Bouyoucos hy-drometer method are shown in table 1.

Aggregate analyses were made by wet-sieving samples containing the equivalent of 50 gm. of oven-dry soil. A nest of three U. S. standard sieves, viz., the 4.0, 2.0, and 0.105 mm. on which the soil had been placed, was operated mechanically in distilled water through a vertical distance of about 2 inches

at the rate of 30 strokes a minute. Results are reported as the percentage of the sample coarser than 0.105 mm.

Swelling measurements were made by a modification of the method proposed by Winterkorn and Baver (14). The apparatus consisted of sections of 50-cc. graduated burettes of essentially the same inside diameter cut into short lengths, care being taken that the glass was cut as squarely as possible. A piece of filter paper was fitted smoothly over the end and tied to the tube. Two grams of the air-dry soil, which had been ground to pass a 100-mesh screen, was placed in each tube fitted with the filter paper. For a given soil the powdered dry material was firmed in the tubes to a uniform volume by moderate jarring. The actual volume varied with different soils. All wetting was done from the bottom by standing the tube in liquid at a uniform depth, lower than the level of the soil in the tubes.

TABLE 2

Relationship of dielectric constant and dipole moment to dispersion of soils in liquids

LIQUID	DIELEC-TRIC CON-STANT	DIPOLE MOMENT $\times 10^{18}$	TURBIDITY OF SUPERNATANT LIQUID 10 MINUTES AFTER SHAKING			
			Geary soil	Cherokee soil	Bates soil	Garden City soil
Water	77.0	1.84	Very cloudy	Very cloudy	Very cloudy	Very cloudy
Ethyl alcohol	25.8	1.63	Cloudy	Cloudy	Cloudy	Cloudy
Ether	4.35	1.14	Very faintly cloudy	Very faintly cloudy	Very faintly cloudy	Very faintly cloudy
Toluene	2.38	0.40	Nearly clear	Nearly clear	Nearly clear	Nearly clear
Benzene	2.28	0.00	Clear	Clear	Clear	Clear

EXPERIMENTAL RESULTS

The qualitative relationship of soil dispersion to the dielectric constant and the dipole moment of a few liquids was observed by shaking vigorously by hand a small quantity of soil in about 2 inches of liquid in a test tube and then allowing the system to stand. The results are recorded in table 2.

The dielectric constants and dipole moments as given in table 2 and subsequent tables are after Getman (5) as far as possible, supplemented by information from Smyth (12) and Sommerman (13).

In making the turbidity readings, special care was exercised to show the influence of the several liquids on a given soil. The intensity of the cloudiness for a given liquid on the several soils varied slightly. It can be noted that the relationship between dispersion and the dielectric constant and the dipole moment of the liquids is distinct and positive. This relationship may be associated with either the ionization or the swelling of the soil particles or with both, since a decrease in the dielectric constant would lower the ionization of the soil particles and, according to Winterkorn and Baver (14), the swelling of soil colloids in the various liquids would be directly related to the dielectric constant.

Effect of prior treatment on stability of aggregates in water

When the organic liquid was poured from the soil, and water was added before the soil had been dried, it was observed that a marked difference in dispersion resulted upon shaking. In order to measure this effect quantitatively, soil samples for aggregate analysis were moistened with various liquids previous to analysis and were wet-sieved in water before the samples had

TABLE 3

Influence of some organic liquids on the stability of aggregates of Geary silty clay loam in water

SOLUTION USED TO WET SOIL PRIOR TO ANALYSIS*	DIELECTRIC CONSTANT	DIPOLE MOMENT $\times 10^{18}$	AVERAGE PORTION OF SOIL COARSER THAN 0.105 MM. ($N = 3$)
			per cent
Sample Ia			
Distilled water..........................	77.0	1.84	60.4
Methyl alcohol, absolute..............	33.7	1.64	80.7
Ethyl alcohol, 95 per cent............	25.8†	1.63†	75.9
Diethyl ether.........................	4.35	1.14	41.7
Toluene.............................	2.38	0.40	13.4
Toluene‡.............................	2.38	0.40	12.2
Benzene.............................	2.28	0.00	14.2
Carbon tetrachloride.................	2.25	0.00	15.1
Sample Ib			
Distilled water.......................	77.0	1.84	49.0
Pyridine............................	....	2.10	43.8
Kerosene............................	2.0–2.2	0.00	12.6
Petroleum ether.....................	....	0.00	13.0
Motor oil, Conoco No. 10............	....	0.00	31.4
Toluene.............................	2.38	0.40	15.4

* Samples wet for 20 minutes with 17 cc. of solution, except diethyl ether which received 20 cc.

† Absolute ethyl alcohol.

‡ Excess of water added after 20 minutes and allowed to stand over night before wet-sieving.

dried. The results of the study with Geary silty clay loam are shown in table 3.

Two samples of Geary silty clay loam were used. Sample Ib was obtained and prepared after the supply of sample Ia was exhausted. The studies with sample Ib were made after most of the other investigations reported in this paper were completed.

All samples moistened previous to analysis, except as otherwise indicated, received 17 cc. of solution, which was allowed to drip slowly from a burette down the side of a slowly rotating Petri dish that held the sample. For those

samples allowed to moisten for 20 minutes, the timing was started when the liquid was added. For the water treatment, it took almost 20 minutes for the center of the sample to become wet; but for the organic liquids, the time required was much less. At the end of 20-minute periods the samples were transferred to the nest of sieves, and the aggregate analysis was made immediately. Because of the rapid evaporation of the diethyl ether the quantity added was increased to 20 cc. The samples thus treated showed no visible evidence of dryness as the soil was lowered into the water.

The most striking results were the low percentages of aggregates retained after previous treatment of the soil with toluene, benzene, carbon tetrachloride, kerosene, and petroleum ether. The similarity in the data from these treatments suggests that their influences were identical. The previous treatment with these solutions resulted in a marked dispersing effect when the samples were subsequently put in water. All these solutions have low dielectric constants and either zero or very low dipole moments. The motor oil, which also has a low dielectric constant and zero dipole moment, caused considerable dispersion but not to the same extent as the above liquids. The oil apparently caused a gumming on the finest sieve, as was indicated by the difficulty in passing water through it during the sieving process. This may account for the higher percentage of soil retained as a result of the oil treatment. The tendency for the pretreatment with the alcohols to increase the stability of aggregates in water as compared to samples receiving prior treatment of water only is also suggested. This tendency is greater for methyl than for ethyl alcohol. The nature of the effect of the alcohols on aggregate stability is in direct relation to their influence on liquid intake by soil colloids as reported by Winterkorn and Baver (14) and to their dielectric constants (5). Though 95 per cent ethyl alcohol was used in this and other experiments, results of supplementary tests indicated that absolute ethyl alcohol would give essentially the same results.

The pretreatment with diethyl ether, though reducing somewhat the stability of the aggregates in water as compared to those samples wet with water before analysis, did not bring about so marked a change as did toluene, benzene, carbon tetrachloride, kerosene, and petroleum ether. The rapid evaporation of the diethyl ether was not the causative factor, since soils kept saturated with ether until placed in water showed essentially the same results. The dielectric constant of diethyl ether is about twice as great as that for either of the above liquids and much less than that for the alcohols. The actual differences in the dielectric constants do not appear to be a satisfactory explanation for the results obtained. The differences in dipole moments do offer a possible explanation, however, since diethyl ether does have an appreciable moment but lower than either methyl or ethyl alcohol, whereas the other liquids exhibit either low or nonmeasurable values. The prior treatment with pyridine resulted in only slightly greater dispersion than with water treatment only.

The fact that the samples treated with toluene for 20 minutes and then supersaturated with water and allowed to stand over night before wet-sieving gave essentially the same result as those samples wet-sieved immediately after the toluene treatment suggests that the dispersion action in water after wetting with toluene is rapid.

The results of a study to determine the influence of wetting with various organic liquids previous to analysis on the stability of aggregates in a number of different soil samples are shown in table 4.

The influence of previous treatment with diethyl ether on the stability of aggregates in water was not determined for all samples of Geary silty clay loam because of the depletion of the supply of prepared soil.

TABLE 4

Influence of prior wetting* with toluene, ethyl alcohol, diethyl ether, and distilled water on the stability of soil aggregates in water

SOIL SERIES	AVERAGE PORTION OF SOIL COARSER THAN 0.105 MM. ($N = 3$)			
	Water	Ethyl alcohol 95 per cent	Toluene	Diethyl ether
	per cent	*per cent*	*per cent*	*per cent*
Geary Ia........................	60.4	75.9	13.4	41.7
Geary I.........................	66.2	78.1	24.1	....
Geary II, first run...............	55.9	62.7	13.2	....
Geary II, second run.............	56.7	60.8	13.9	....
Garden City†....................	39.0	51.1	26.7	48.4
Cherokee.......................	33.7	62.8	22.1	61.2
Bates...........................	68.7	80.6	59.9	73.8
Average, $N = 7$...............	54.4	67.4	24.8	....
Average, $N = 4$...............	50.5	62.6	30.5	56.3

* Samples moistened for 20 minutes before analysis.
† Series not identified.

Again the prior treatment with toluene increased the dispersion of the soils, as indicated by the lower percentage of the sample retained when compared to the samples previously treated with water, ethyl alcohol, and diethyl ether. The increase in dispersion is marked for all soils, but is relatively less for the Bates. The failure of the Bates to disperse as completely as the other soils may be partly explained on the basis of the coarser texture of the soil. The pretreatment with ethyl alcohol increased the stability of the aggregates in water in every instance, when compared to those samples treated for 20 minutes with distilled water. The prior treatment with diethyl ether resulted in slightly greater dispersion than that caused by the ethyl alcohol.

A qualitative study of the influence of previous wetting of soil with toluene on the ease with which the soil dispersed in water was made on 9 air-dry samples sent to the laboratory by farmers for soil-testing purposes. These came from

widely differing soil areas within the state. With all soils, the wetting with toluene resulted in a greater dispersion in water than when similar samples were treated only with water, thus indicating that the treatment is a rather good dispersing agent for many soils.

Since the increased dispersion of soils in water is rather marked as a result of first wetting the dry soil with toluene, benzene, carbon tetrachloride, kerosene, or petroleum ether, it appears that one of the binding forces responsible for aggregate stability is weakened as a result of the treatment. It further appears that the binding force so disrupted is of major importance in maintaining a stable aggregate.

Effect of leaching with toluene on stability of aggregates

In an attempt to find an explanation of the influence of toluene on the stability of aggregates, some samples were leached with toluene and some leached

TABLE 5

Effect of leaching with toluene on the stability of Geary soil (sample Ib) in water

TREATMENT*	AVERAGE PORTION OF SOIL COARSER THAN 0.105 MM. ($N = 3$)
	per cent
Untreated, dried on steam bath.............................	44.4
Leached with toluene, dried on steam bath..................	40.4
Leached first with toluene, then with distilled water, dried on steam bath...	49.4

* All samples wet-sieved without prior treatment with water.

first with toluene followed by water, after which all the samples were dried on a steam bath before wet-sieving. The results are shown in table 5.

The leaching of the soil with toluene and subsequent drying on a steam bath did not change the appearance of the samples. The aggregate analysis also revealed only a slight change in the percentage of the sample coarser than 0.105 mm.

Those samples leached first with toluene, followed immediately with water, showed a very marked change in appearance. The water caused an almost immediate dispersion of the samples to the extent that leaching under suction became difficult. The soil mass, on drying, aggregated into large hard clods with relatively great shrinkage. No evidence of the originally desirable aggregates was discernible. Wet-sieving showed that even a greater proportion of the soil was retained as aggregates coarser than 0.105 mm. than was present in the original sample.

Since there is no evidence of a dispersing action in water resulting from the toluene treatment, once that organic liquid is removed from the soil, it appears that the effect of toluene on dispersion is due to the presence of the toluene in the soil at the time the soil makes contact with water.

Swelling studies

The influence of several prior treatments on the swelling of soils in water was studied by allowing 2 gm. of air-dry soil in graduated tubes to stand in a given liquid for 20 minutes and then transferring the tubes immediately into distilled water where they were left for 24 hours. The influence of water, methyl alcohol, ethyl alcohol, diethyl ether, pyridine, and toluene on the swelling in water of the soil types used in this study is shown in table 6.

The swelling data represent the increase in volume occupied by the sample during 24 hours of wetting with distilled water over the original volume occupied by the dry soil. For a given series the 2-gm. sample was firmed to a constant volume. The data should not be considered as expressing the absolute swelling values for a given soil. It is thought, however, that the differences

TABLE 6

Effect of prior wetting with organic liquids on the swelling of soils in water

SOIL SERIES	VOLUME OF 2 GM. DRY SOIL	AVERAGE SWELLING IN WATER AFTER TREATMENT WITH* (N = 4)					
		Ethyl alcohol	Methyl alcohol	Pyridine	Distilled water	Diethyl ether	Toluene
	cc.	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Garden City†	1.6	6.3	8.1	12.5	13.1	15.6	18.8
Geary	1.8	7.2	9.4	7.2	10.0	13.9	15.6
Cherokee	1.6	7.5	6.9	10.0	9.4	6.3	16.3
Bates	1.4	10.0	10.0	10.0	14.3	30.0	17.1
Average		7.8	8.6	9.9	11.7	16.5	17.0

* Soils wet for 20 minutes with the indicated liquid, then placed immediately in distilled water.

† Series not identified.

between treatments indicate, relatively, the influence of previous treatment on the swelling of individual soil types.

The most obvious results of the studies were consistent and relatively large increases in the percentage of swelling in water following pretreatment of the soils with toluene and diethyl ether as compared with pretreatment with distilled water. In addition, there were nearly correspondingly great decreases in the percentage of swelling in water resulting from previous treatment with methyl and ethyl alcohol. The only exception to this generalization was the relatively slight swelling of Cherokee silt loam when treated with diethyl ether. It appears, therefore, that these liquids exert a rather marked influence on the swelling of soils in water—toluene and diethyl ether falling in one group, and the alcohols in another.

The results of the swelling studies indicate some relationship between swelling and dispersion of soils in water after pretreatment with the indicated liquids. This substantiates the work of Lutz (6), who found that differences

in swelling would partly explain the extent to which soils are aggregated into water-stable granules. There are some obviously unrelated results suggesting that swelling is not the only factor involved in dispersion. If only methyl alcohol, water, and toluene or ethyl alcohol, water, and toluene are considered, the two factors, viz., swelling and dispersion, show a distinctly positive relationship. When the effects of methyl and ethyl alcohols are compared, it is found that ethyl causes slightly less swelling but slightly greater dispersion than methyl. This difference in swelling in water, caused by pretreatment of the soils with alcohols, is in the same order as the swelling differences noted by Winterkorn and Baver (14) for soil colloids in pure alcohol without the intervening effect of water. It appears, therefore, that the swelling difference noted in this experiment is purely the effect of the adsorbed alcohols. Thus, the lower dispersion of soil first treated with methyl alcohol, when compared with ethyl alcohol treatment, may be due to a greater increase in the size of soil aggregates as a result of greater swelling in methyl alcohol. This possibility, together with the greater stability of soils in alcohol as compared to soils in water, might account for the relative differences in the dispersion of soils in water following treatment with water and with methyl and ethyl alcohols.

The influence of diethyl ether on dispersion and swelling should be noted. Wetting the soils with diethyl ether before placing them in water had nearly as great an effect on swelling as did toluene wetting, yet it caused much less dispersion. Its effect on dispersion was somewhat less than that of water used as a previous treatment, when all soils are considered.

Pyridine caused greater dispersion but less swelling than water alone.

According to Winterkorn and Baver (14) the intake of liquid by soil colloids and their tendency to cause swelling is in the order: water > methyl alcohol > ethyl alcohol > toluene. The tenacity with which the sorbed liquid molecules are held by the soil should be expected to be in the same order as the quantity of liquid sorbed by the soil, which is directly related to the dipole moments of the liquids. Diethyl ether, on the basis of its dipole moment, would be expected to fall between ethyl alcohol and toluene in the above series, whereas pyridine should come before water.

When a soil is placed in water after the adsorption surfaces have been occupied by the organic liquid molecules, it would be expected that the ease with which water molecules could replace the molecules of the organic liquids would be in the order: toluene > diethyl ether > ethyl alcohol > methyl alcohol > pyridine. Thus, at the end of 24 hours in water, at which time final swelling readings were made, the soil may hold only a limited quantity of toluene but may hold an appreciable quantity of oriented alcohol molecules and pyridine, which could not be replaced by water molecules.

The relative ability of the water molecules to displace the organic molecules from the soil is indicated in a qualitative manner by the color change that took place after addition of the water. For the soils used in this study, the presence

of the organic liquids gave to the soil a dark gray to black color. In water alone, the color was always a lighter shade, approximating a brownish gray. The addition of water to the pyridine- and alcohol-wet samples did not change appreciably the color of the soil. Water added to the toluene-wet samples caused an immediate change from nearly black to a brownish gray of approximately the same shade as, but slightly lighter than, that of the soil treated only with water. Water added to the samples wet with diethyl ether caused a change in color somewhat intermediate between that of the alcohol- and the toluene-wet samples but more closely resembling the color change associated with the toluene treatment. The color was slightly darker than that of the soil wet only with water. On the basis of color change, the indications are that most of the toluene was displaced by the water, whereas only a limited amount of the pyridine and alcohols was displaced, with the diethyl ether falling between these two extremes.

Pyridine interacted more strongly with the soils than did any of the other liquids used, as indicated by the readily observed heat of wetting. Because of the strong interaction with the soil, water would probably be unable to replace a large proportion of pyridine. The swelling in water of soils previously treated with pyridine, therefore, probably would be governed largely by the extent of swelling in the organic liquid.

Since alcohol causes less swelling than water, any space occupied by alcohol would tend to reduce the swelling in water in comparison to swelling in water without pretreatment with alcohol. Swelling studies also indicate that little if any of the oriented alcohol was displaced during the swelling period. Thus, in a supplementary experiment, the average percentage increase in volume of triplicate samples of the four soils at the end of 24 hours' contact with ethyl alcohol was 8.3. In contrast, the average percentage increase in volume of quadruplicate samples of the same soils wet first with alcohol and then placed in contact with water for 24 hours was 7.8, as recorded in table 6. The average swelling of triplicate readings on each of the four soils after 24 hours' contact with toluene was 7.4 per cent in contrast with 17.0 per cent as the average of quadruplicate readings on all soils, as reported in table 6, where the 20-minute toluene treatment was followed by 24-hour contact with water. Thus, the swelling in water after treatment with toluene is not determined by toluene directly but by the influence of the solvent on some soil constituent which had previously hindered the swelling. In contrast, water alone resulted in 11.7 per cent increase in volume at the end of 24 hours.

The possible explanation for the failure of the diethyl ether treatment to result in as great a dispersion as would be indicated by its great effect on swelling may be associated with the appreciable dipole moment of diethyl ether in contrast with the low dipole moment of toluene. Because of this property, diethyl ether should be strongly adsorbed by orientation of the molecules, whereas toluene should be adsorbed to a lesser extent. When once occupying completely the adsorption surfaces of the soil, the water, even though in excess,

may not be able to replace all the adsorbed diethyl ether. Since the diethyl ether would be less strongly adsorbed than methyl or ethyl alcohol, it should be more easily replaced than either of the alcohols. Under similar conditions, therefore, the water should be able to replace more of the diethyl ether than of the alcohols. It is possible that enough diethyl ether was replaced by the water to permit nearly maximum swelling in the water. Since diethyl ether is only slightly soluble in water, any of its molecules on the adsorption surface would reduce the solubility of the adsorbed layer in the intervening water. Probably, the solubility of the adsorbed layer in the dispersing liquid is essential for dispersion. If the two liquids are non-miscible, or only slightly miscible, the attraction between the soil particles, even though reduced to a low value, may still be greater than the attraction of the soil particles through the adsorbed liquid layer to the dispersing medium.

The cause of the dispersing effect of toluene, benzene, carbon tetrachloride, kerosene, and petroleum ether, when soils moistened with them are placed in water, is not clear. Perhaps it is due to the increased solubility of certain fractions of the soil, which would include fats and waxes, that would normally protect the soil aggregates from complete wetting.

That it is not a case of complete solution of a constituent, such that it can be removed permanently by leaching, is suggested by the fact that leaching with toluene and subsequent drying prior to wet-sieving in water did not result in marked dispersion. It may be, however, that a material that would affect the soil aggregates in a similar manner was formed or deposited after removal of toluene by drying. It is known that glass cleaned with xylol or similar substances will not remain clean indefinitely but on drying will again accrete rather quickly a coat that resists wetting with water. Perhaps it is the result of a change in the surface energy of certain soil components that might cause a greater interaction of the soil with the water. Preliminary results indicate that the action of toluene in bringing about subsequent dispersion in water may be specific for the mineral fraction of the soil and not for the organic fraction.

There may be some similarity between the effect of toluene and diethyl ether on the soil–water system and the effect of these liquids on a quartz–sand–motor-oil–water system. In the latter system, shaking will not result in an emulsion, neither will the sand remain suspended. The addition of diethyl ether did not change the physical appearance of the system, but the addition of toluene made possible the formation of a semipermanent emulsion with a suspension of the sand grains in the oil globules.

SUMMARY AND CONCLUSIONS

A study of the stability of soil aggregates in liquids of varying dielectric constants showed that the two variables were inversely related.

Wetting air-dry soils for 20 minutes with toluene, benzene, carbon tetra-

chloride, kerosene, and petroleum ether, and wet-sieving in water while the soils were still wet with the organic liquid resulted in a marked dispersion of the aggregates. The marked dispersing effect resulted only when the soil was wet with the liquid at the time contact was made with the water.

Treatment of air-dry soils with ethyl and methyl alcohols before wet-sieving in water increased the percentage of water-stable aggregates larger than 0.105 mm., whereas previous treatment with diethyl ether decreased slightly the percentage of water-stable aggregates larger than 0.105 mm., as compared to pretreatment with water only.

Swelling measurements showed that pretreatment with ethyl and methyl alcohols decreased the swelling of soils in water at the end of 24 hours in comparison to those samples wet only with water. Pretreatment with either toluene or diethyl ether caused a marked increase in swelling in water.

Dispersion is associated with the swelling of soils although some exceptions to the general relationship indicate that swelling will not alone explain dispersion.

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STUDIES OF CLAY PARTICLES WITH THE ELECTRON MICROSCOPE: I. SHAPES OF CLAY PARTICLES[1]

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Because of uncertainty in the establishment of the physical properties of clay minerals, the soil scientist has been at a disadvantage in interpreting data from studies on the clay separate. It has been his problem to establish the relationship between the highly developed surface characteristics of the clay minerals and their structure. A knowledge of the shapes of the particles in question would be invaluable.

In ordinary light microscopy it is impossible to resolve the detail desired in the smaller separates of the soil. The development of the electron microscope gives a means of extending the observation range by a factor of 50 to 100, with possible further extensions in the future. Details on the construction and operation of the microscope have been adequately covered in the current literature.[3]

The great advantage of an electron optical system lies in its highly increased resolving power. With the present-day practical apertures, one should expect the best resolving power to be about 20 Å., or a corresponding useful magnification of about 100,000 diameters. With small apertures, the depth of focus is many times greater than that of the highest power light microscopes.

In electron microscopy the image formation is due to a scattering of the electrons. Because of the necessity of the transmission of the electron beam, the glass slides used in light microscopy must be replaced by extremely thin films as specimen holders. The images observed on a fluorescent screen or on a photographic plate are due to differences in thickness and in density of the specimen.

MICROSCOPE TECHNIQUE

Since electron scattering is proportional to the thickness and density of the substance through which the beam is passed, it is absolutely essential that the films supporting the specimens be extremely thin and homogeneous.

[1] Contribution from the department of agronomy, Ohio State University.

[2] Graduate Assistant and Assistant Professor respectively. The authors are indebted to A. Prebus and J. Dankworth for assistance in the operation of the microscope.

[3] Marton, L. 1941 The electron microscope. A new tool for bacteriological research. *Jour. Bact.* 41: 397–413.

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In preliminary investigations air-dry clay was ground in an agate mortar with viscous butyl cellosolve and then diluted with amyl acetate to give the desired thickness of the film. The results of these studies were satisfactory, but because of possible criticism on the treatment of the clay minerals, other methods were studied.

The technique showing the most promise involves the drying of a <1 per cent suspension of clay in water on a previously dried film of butyl cellosolve in amyl acetate (approximately 2 per cent). The films are prepared by spreading one drop over a perfectly clean and quiet water surface. After evaporation of the solvent a thin film (<100 Å.) remains on the water surface. Small disks (2 mm. diameter) of 200-mesh copper screen that have been carefully rolled to extreme thinness are dropped upon the film. The film with the copper screen acting as a mechanical support is retrieved with suitable holders and placed upon a drying rack. The copper screen holding the film is placed upon a clean blotter and a drop of clay-water suspension is allowed to dry on the surface of the film. The disk supporting the film containing the clay is placed in the specimen holder and then into the vacuum chamber of the microscope for observation.

RESULTS

Plate 1, figure 1, shows several well-defined plate-shaped minerals weathered from the basic igneous dikes in the Ozarks of Missouri. In the upper right hand corner of the plate a wrinkle in the film gives a three-dimensional view of one of the plates. From the magnification given, the thickness of this plate-shaped particle was calculated to be in the neighborhood of 400 Å.

A series of three photographs was taken of a crystal of dickite[4] from Chihuahua, Mexico. In plate 1, figure 2, the crystal is lying flat; in figure 3, at an angle of about 45°; and in figure 4, it is standing approximately on edge. During the 15-second exposure the particle vibrated considerably. The authors realize that this dickite crystal is slightly above the upper limit of the colloidal range, but the series was included to show detail in crystal habit. An aggregate of dickite crystals entirely within the colloidal range is presented in figure 5 and shows similar shapes and crystal form. This series of photographs substantiates the beliefs of Marshall[5] and others regarding the plate-shaped nature of clay particles.

Rod-shaped particles were not uncommon in the clays examined. Figure 6 shows several typical rods. The penetration of the electron beam shows these particles to be rods and not plate-shaped particles on edge.

Preliminary investigations comparing different types of clay minerals show

[4] Samples of dickite, kaolinite, and montmorillonite were taken from the collection of C. E. Marshall.

[5] Marshall, C. E. 1941 Studies in the degree of dispersion of the clays: IV. The shapes of clay particles. *Jour. Phys. Chem.* 45: 81–93.

distinct differences.   Plate 2 shows characteristic crystals of kaolinite and montmorillonite.   The crystallinity of kaolinite is many times better developed than that of montmorillonite.   In contrast to the kaolinite, the montmorillonite presents a fluffy appearance, which may serve to explain the more highly developed surface properties of the 2:1 type of clay minerals.

CONCLUSIONS

The electron microscope has been presented as a new tool for soils research.

A series of photographs substantiate the beliefs of many workers in the plate-shaped nature of clay particles.

Preliminary investigations show the crystallinity of kaolinite to be many times better developed than that of montmorillonite.   Further investigations are being conducted by the authors to characterize the different types of clay minerals.

PLATE 1

ELECTRONMICROGRAPHS OF PLATE-AND-ROD-SHAPED CLAY PARTICLES AND OF DICKITE CRYSTALS

Distance between marks in each figure represents 1μ

FIG. 1. Plate-shaped clay particles weathered from the basic igneous dikes in the Ozarks of Missouri.

FIG. 2. Dickite crystal lying flat.

FIG. 3. Same dickite crystal lying at an angle of about 45°.

FIG. 4. Same crystal standing approximately on edge.

FIG. 5. Aggregate of dickite crystals showing characteristic shapes and crystal habit.

FIG. 6. Typical rod-shaped particles.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5
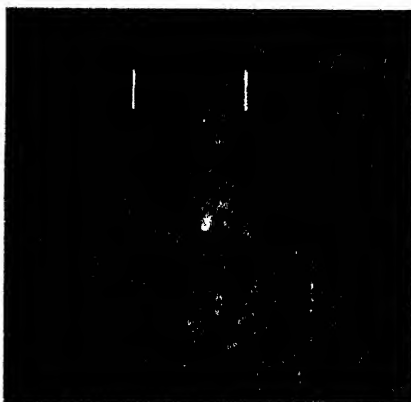
Fig. 6

PLATE 2

ELECTRONMICROGRAPHS OF KAOLINITE AND MONTMORILLONITE CRYSTALS

Distance between marks in each figure represents 1μ

FIG. 1. Characteristic crystals of kaolinite.

FIG. 2. Characteristic crystals of montmorillonite.

FIG. 1

FIG. 2

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